Theoretical/Best Practice Energy Use In Metalcasting Operations

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Errata Sheet

This is a listing of the corrections that were made since the original posting of the *Theoretical/Best Practice Energy Use In Metalcasting Operations* in April 2004.

Text Errors

- Cover, in the title Metal Casting was two words and changed to one word "Metalcasting".

- Page 9, the following sentence was inserted. "This study, therefore, utilized actual metalcasting energy usage by facility type to calculate the total energy used by alloy, rather than summaries of energy consumption data by NAICS codes."

- Page 9, the following sentence was removed: "It is estimated that the industry consumes 466 trillion Btu tacit energy annually."

- Page 10, Table 9, the total 2003 row was deleted.

- Page 52, Table 31, removed total row and re-labled header on second column to "2003 Benchmark Tacit Energy."

- Page 52, Table 32 removed total row and re-labled second column to "2003 Benchmark Tacit Energy."

- Page 62, Table 37 was removed and tables 38 through 56 where renumbered accordingly.

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EXECUTIVE SUMMARY

The energy used to melt one ton of metal in a metalcasting facility is significantly higher than the theoretical minimum requirements. The theoretical requirements can be calculated for melting and annealing processes. The large variety of other casting processes and value added work performed at some casting facilities, however, makes it difficult to calculate the theoretical minimum requirements for the entire facility. Energy use also varies widely among facilities with differing sales volumes and dissimilar production castings for different end use market segments.

This study determined the theoretical minimum energy requirements for melting processes for all ferrous and nonferrous engineering alloys. Detailed energy consumption data for best practice melting methods were only available for three processes: Iron Induction Melting, Iron Cupola Melting, and Aluminum Reverberatory Melt Furnaces. Comparative data for the three processes are summarized in Table 1 and covered in detail in Chapter 1.

Table 1 - Comparison of Practical Minimum, Theoretical Minimum and Best Practice Minimums for Selected Processes (Delivered kWh/Ton Melt)

Selected Processes	Theoretical Minimum	Industry Average	% Difference	Best Practice Minimum	% Difference	Tacit Best Practice Minimum
Iron Induction Melting	351.5	796.3	56%	538.1	35%	1,689.5
Iron Cupola Melting	351.5	1,413.6	75%	1,002.5	65%	1,124.5
Aluminum Reverberatory Melt Furnaces	288.7	1,399.8	79%	510.5	43%	523.2

These best practice melting processes include iron and aluminum castings production. Iron and aluminum castings production accounts for 84 percent of the total castings produced in the United States and 82 of the tacit energy used by the casting industry sector. Tacit energy is a term used to describe an energy value that equals the combination of onsite energy consumption, the process energy required to produce and transmit/transport the energy source, and feedstock energy.

Table 1 gives the theoretical minimum energy requirements to melt one ton of metal, ignoring all efficiency loses, along with the industry average and the best practice. The best practice is considered the minimum energy required to melt one ton of metal at an operating foundry. The last column of Table 1 gives the tacit energy requirements in addition to the delivered energy, which is used to compare individual melting processes.

Energy reduction opportunities that are not melting related are also covered in detail in this report. All major process steps identified as having significant energy reduction opportunities are summarized on Table 2. The details of this analysis are covered in the body of this report. Table 2 is based on tons shipped, not tons melted, because many of the process steps selected have an effect on overall facility energy use, not just melt energy.

The potential energy reduction opportunities listed in Table 2 include a combination of facility- related improvements and work practice changes. The facility-related changes will evolve more slowly as energy costs rise and aging equipment is replaced or modified. The efficiency improvements listed are combinations of work practice and scheduling improvements that can affect energy usage, as well as other facility-related expenses. The yield improvements are long-term efforts requiring investments in software development and training of plant personnel to take advantage of the latest solidification modeling programs.

Table 2 - Potential Energy and CO_2 Emission Reductions

Process	Tacit kWh/Ton Ship	Tacit 10^6 kWh/Year	Tacit 10^{12} Btu	Affected Ship Tons/Year*	Tacit kWh/$ Sales*	CO_2 10^3 Tons/Year
Iron Induction Melting	2,253	4,621	15.78	2,050,690	2.01	1,050
Iron Cupola Melting	937	4,553	15.55	4,860,895	0.83	1,254
Aluminum Reverberatory Melt Furnaces	1,559	3,174	10.84	2,036,700	0.37	633
Casting Yield Improvements	478	6,647	22.70	13,904,000	0.25	1,471
Operating Efficiency Improvements, Aluminum	2,797	6,329	21.61	2,263,000	0.66	1,240
Heat Treat Improvements, Ductile Pipe and Steel	200	650	2.22	3,257,660.0	0.11	127.0
Ladle Heating Improvements	282	3,915	13.37	13,904,000.0	0.15	767.0
Total Potential Savings		**29,889**	**102.07**			**6,542**

*Affected Tons shipped are shipments from facilities making improvements to Best Practice, not total alloy shipments.

The potential energy and carbon dioxide (CO_2) emission reductions shown in Table 2 are significant. The 102.07 10^{12} Btu of tacit energy represents a 21.9 percent reduction in energy use, while 6,542 10^3 tons of CO_2 represents a 21.6 percent reduction in CO_2 emissions per year at 2003 forecast production levels.

An analysis of the potential application of combined heat and power (CHP) technology to casting process waste heat is also evaluated in this report. This analysis is provided in Chapter 3, Section 2 and concludes that the waste heat generated by best practice cupola-melting furnaces may justify CHP applications and, to a much lesser extent, high temperature, heat-treat operations. Site-specific operating conditions should be factored into potential savings and cost analysis to justify capital investments.

INTRODUCTION

OBJECTIVE

The objective of this study is to evaluate the theoretical and practical potential for reducing energy requirements to produce one ton of molten metal (cast iron, steel, aluminum, magnesium, zinc and copper) and the associated carbon dioxide (CO_2) emissions in metalcasting operations.

RESEARCH METHODOLOGY

This study is focused on determining the practical potential for reducing energy requirements in the metalcasting industry by looking at industry best practices, which are referred to as "best practice minimums." Both equipment design efficiencies and operating procedures related to reduced-energy consumption are discussed in detail. The highest energy consuming processes within each casting alloy family were investigated to determine the potential for energy reduction measures.

The "**theoretical minimum**" energy requirements are also calculated for the major energy consuming processes. The theoretical minimum energy requirements are calculated by ignoring all energy losses and therefore are not achievable in practice. A baseline of current foundry energy usage was also determined from the best available information and is referred to as the "industry average." The **industry average energy usage** was then compared to the **best practice** to determine the potential for energy reduction using existing and proven technologies and procedures. The results are stated in both **tacit energy** Btu per ton of metal shipped, as well as estimated carbon dioxide (CO_2) emission reductions and energy cost per ton shipped.

The analysis of energy requirements for casting processes is stated in "tacit" energy units. This is the energy required to produce and deliver the form of energy used by the facility, and not just the energy delivered to the site. Table 3 lists the tacit energy conversions for the different forms of energy used in metalcasting operations, as well as the net energy content traditionally used for this type of analysis.

Table 3 illustrates that the conversion of coal to electricity and the transmission losses associated with delivering this form of energy to the metalcasting facility results in significant losses. Approximately 10,500 Btu are required to deliver 3,412 Btu of usable energy to the facility, a loss of approximately 68 percent. This inefficiency is somewhat offset because most uses of electricity within the facility have a much higher energy conversion efficiency than either natural gas or **coke**. The listing of oxygen in Table 3 illustrates that purchasing oxygen for use within a metalcasting facility is in itself energy consuming. It is listed in this report for best practice comparison purposes. Many facilities use oxygen to improve overall melting efficiencies, but oxygen also has an impact on tacit energy consumption and CO_2 emissions associated with its use.

The recommendations for achieving reduced energy consumption are primarily focused on tacit energy conservation and accompanying CO_2 emission reductions, rather than cost. In most cases, reducing energy consumption will reduce cost, but local conditions affecting the cost per Btu for different forms of energy will sometimes be contrary to energy conservation efforts. In other cases, the investment required to purchase the most energy efficient equipment or plant technical expertise may discourage the most energy efficient processes.

Table 3 - Key Energy Conversion Factors				
Energy Form	**Energy Content**		**Tacit Energy**	
Coke	13,000	Btu/lb	14,000	Btu/lb
Electricity	3,412	Btu/kWh	10,500	Btu/kWh
Natural Gas	1,000	Btu/scf	1,026	Btu/scf
Oxygen	61	Btu/scf	175	Btu/scf

Metal Casting Energy and Environamental Profile, DOE, 1999(4)
Annual Energy Outlook 2003, EIA, 2003(36)

Results of the energy analysis performed for this report are also stated in CO_2 emissions. Table 4 summarizes the estimated CO_2 emission rates for different forms of energy.

Table 4 - CO_2 Emission Factors by Energy Type		
Energy Source	**Pounds of $CO_2/10^6$ Btu**	**Tacit Energy Pounds of $CO_2/10^6$ Btu**
Electricity	418.74	136.19
Coke	185.36	172.12
Natural Gas	117.60	114.73

Notes: CO_2 emission factors from DOE 1999 Profile quoting EPA 1995 and DOE 1977 P. 44., APEC Region Options to reduce CO_2 Emissions, DOE & EPA July 2000, and EPA AP-42. (4)(6)

Literature searches were conducted to obtain available information on energy conservation in the metalcasting industry. The specific processes being investigated for energy reduction potential include those listed in Table 5. The Department of Energy (DOE) report, "Energy Use in Selected Metalcasting Facilities,"(2) (Eppich Technologies, 2003) was particularly helpful in determining the current energy profile of the casting industry. Casting forecasts and historical information were obtained from the report "2003 AFS Metalcasting Forecast & Trends" (Stratecasts, Inc., 2003)(1). Industry groups that participated in this study include the American Foundry Society, Steel Founders Society of America and the North American Die Casting Association. These organizations, industry experts, and casting equipment suppliers were interviewed to determine what they consider best practice. Casting facilities personnel and industry equipment suppliers identified as best practice, were interviewed, and many were visited to capture actual energy usage information and so that operating personnel could be interviewed. Technical contributions were also provided by Technikon, LLC of Sacramento, California and Eppich Technologies of Parma, Ohio. The **combined heat and power (CHP)** analysis was provided by EnVise, LLC, of Madison, Wisconsin.

Throughout this report, several comparisons are drawn between research report findings and specific calculations performed as part of this study. Different sources of data did not always use the same bases for the theoretical energy requirements to melt a ton of metal, and therefore the resulting energy calculations are slightly different in some comparisons. It appears this is the result of using different theoretical energy calculations, depending on the alloys of the metals being melted. This report does not attempt to rectify these minor differences.

Table 5 - Energy Study Metal Casting Operations			
Alloy		**Melting Method**	**Casting Method**
Cast Iron	Gray Iron	Cupola	Greensand
		Induction	
	Ductile Iron	Cupola	Greensand
		Induction	
		Cupola	Centrifugal (Pipe)
Steel		Arc (EAF)	Greensand
		Induction	Airset
Aluminum		Gas	Lost Foam
			Permanent Mold
			Die Casting
		Electric	Die Casting
Zinc		Gas	Die (Hot Chamber)
Magnesium		Gas	Die (Cold chamber)
Copper		Gas	Greensand

METALCASTING INDUSTRY PROFILE

The casting industry has experienced back-to-back years of declining sales and profits. Many casting suppliers have been forced to close or "mothball" facilities. Despite these recent declines, the casting industry as a whole was expected to expand moderately in 2003 and grow annually for the next five years. Many market sectors are expected to consume metalcastings in peak quantities in the coming years, although others will decline due to technological and material change. (1)

The U.S. Metalcasting Industry is currently comprised of approximately 2,620 metalcasting facilities, a continuing downward trend. As recently as the year 2000 there were about 2,800 facilities. The vast majority of the tonnage is produced in the fewer, larger facilities. The industry is also experiencing a consolidation of ownership. The capacity of the metalcasting industry is currently estimated to be 79 percent of maximum output. (1)

Table 6 - Estimated 2003 Production Level*

Alloy Produced	Ship Tons Per Year	% of Total Tons	Sales Dollars
Cast Iron	9,493,936	68%	$10,453,213,920
Steel	1,257,660	9%	$3,742,796,160
Aluminum	2,263,000	16%	$9,564,143,000
Copper Based	279,480	2%	$1,293,140,000
Zinc	419,220	3%	$756,800,000
Magnesium	139,740	1%	$671,580,000
Other	50,964	1%	NA
Total	**13,904,000**	**100%**	**$26,481,673,080**

* AFS Metal Casting Forecast and Trends 2003. (1)

Industry of the Future 2002 Annual Report, DOE (3)

Casting shipments were forecast to increase in 2003 to approximately 13,904,000 tons, from a low of 13,070,000 in 2001. A profile of the forecast casting shipments by alloy type for 2003 is shown in Table 6. Casting shipments are expected to continue this increasing trend through 2008 and 2009 when they are expected to reach a peak of 16,400,000 tons. The increase in demand in 2003, coupled with expected recoveries in Europe and Asia, are forecast to increase imports as well as exports. Both will greatly affect the shipments of castings in the individual market. (1) This increase in casting production levels through 2009 will result in increased energy usage, as well as CO_2 emission levels.

Table 6 shows that cast iron shipments were expected to be 68 percent of metalcasting shipments for 2003, followed by aluminum castings at 16 percent. Steel castings are third at 9 percent, with other nonferrous alloys produced in much smaller quantities. On the basis of sales dollars, cast iron represents 39 percent of casting sales, while aluminum is 36 percent and steel 14 percent. Cast iron production can also be further characterized into three distinct iron types, gray iron, ductile iron, and malleable iron, as shown in Table 7. Malleable iron is rapidly being replaced by ductile iron and other metal production processes; therefore, this report does not discuss malleable iron and consolidates the tons shipped into the gray iron category.

Table 7 - Estimated 2003 Cast Iron Production*

Cast Iron Produced	Tons Per Year	% of Total Tons	Sales Dollars
Gray Iron	5,393,964	57%	$5,401,118,688
Ductile Iron	4,016,128	42%	$5,052,095,232
Malleable Iron	83,844	1%	NA
Total	**9,493,936**	**100.0%**	**$10,453,213,920**

* AFS Metal Casting Forecast and Trends 2003. (1)

The casting industry's end use market is described in Table 8 and is led by the automotive and light truck market, with 35 percent of total production. The automotive and light truck castings have traditionally been cast iron, but in recent years the industry has been moving to aluminum engine castings and other nonferrous alloys, such as magnesium.

Table 8 - Metal Casting End Use Markets (Ship Tons)*

End Use Market	Market Share
Automotive & Light Truck	35%
Pipe & Fittings	15%
Construction, Mining & Oil Fields	6%
Internal Combustion Engines	5%
Railroad	5%
Valves	5%
Farm Casting	3%
Municipal Castings	3%
Other	23%

*American Foundry Society 1998. Energy and Environmental Profile, DOE 1999(4).

ESTIMATED ENERGY USE IN THE METALCASTING INDUSTRY

The metalcasting industry is, by nature, very energy intensive. Metalcasting processes include melting, remelting, and heat treating castings, which are very energy intensive processes. The delivered energy used by metalcasting facilities in the United States was determined to be 236 trillion Btu in the Manufacturing Energy Consumption Survey of 1998 at production volumes similar to 2003.(45) This delivered energy level is confirmed by the metalcasting energy profiles listed in Appendix A.

The industry is also a major recycler of scrap metals. In ferrous casting facilities, over 90 percent of the raw materials melted have been used previously in a casting or sheet metal part of some type. Nonferrous castings of aluminum and magnesium have seen significant demand increases in recent years due to the need to produce lighter automobiles and light trucks for improved fuel economy. This demand for lighter materials has also carried over to the

Department of Defense, which is moving toward a lighter, more mobile military force. These nonferrous casting facilities use a higher level of materials supplied by primary metal facilities due to the recent increases in their production volumes and the resulting lack of scrap materials available from scrap metal processors.

Many studies have been undertaken during the last fifteen years to determine the energy profile of the metalcasting industry, with varying results. Many different types of molding and melting processes are used by this industry, and very few facilities are exactly alike. Many casting facilities have other value-added processes onsite in addition to foundry operations. It is difficult to capture all of the energy usage associated with casting specific processes. Studies using the North American Industry Classification System (NAICS) codes to identify facilities fail to pick up co-located casting facilities; in other cases, studies have incorrectly associated the value-added process with casting process energy usage.

Literature searches conducted for this study provided many documents written by the metalcasting industry and federal government agencies. The specific documents referred to for relevant casting energy data are listed in the reference section of this report. A significant study that yielded very accurate energy data for a specific number of facilities is the "Energy Use in Select Metalcasting Facilities," which was a quantitative study that performed onsite measurement of energy use.(2) The study gives energy profiles for a cross section of casting facilities and was used along with other foundry-specific studies to produce Table 9. This study, therefore, utilized actual metalcasting energy usage by facility type to calculate the total energy used by alloy, rather than summaries of energy consumption data by NAICS codes. The specific facility profiles described in this study, along with information collected during the investigative phase of this study, were used to develop the energy estimates by alloy. This is documented in Appendix A and summarized in Table 9.

Table 9 - Estimated 2003 Metal Casting Energy Usage & CO_2 Emissions

	Tacit Energy 10^6 Btu/Ship Ton	2003 Estimated Ship Tons**	2003 Benchmark Tacit Energy 10^{12} Btu	Tons 10^3 CO_2
Gray Iron	29.7	5,477,808	162.6	11,187
Ductile (Other than pipe)	26.0	2,016,128	52.4	3,494
Ductile Iron Pipe	7.8	2,000,000	15.7	1,160
Steel	36.5	1,257,660	45.9	2,993
Al High Pressure Die Casting	60.6	1,585,720	96.0	6,217
Al Permanent Mold/Sand	99.4	373,266	37.1	1,372
Al Lost Foam	81.9	304,014	24.9	1,613
Mg Die Casting	67.8	106,600	7.2	486
Zinc Die Casting	23.4	344,000	8.0	515
Copper-Base; Sand	37.3	311,600	11.6	780
Titanium: Investment; Induction; HIP*	65.0	40,977	2.7	187
Other Non-Ferrous*	22.5	86,227	1.9	353

*Not evaluated in this analysis.

**AFS Metal Casting Forecast and Trends 2003. (1)

Breaking down this information into tacit kWh per ton and energy cost per sales dollars is shown in Table 10. Energy dollars as a percent of sales vary from 4 percent for copper-based sand castings to 14 percent for gray iron castings.

Table 10 - Estimated 2003 Metal Casting Energy and Sales*

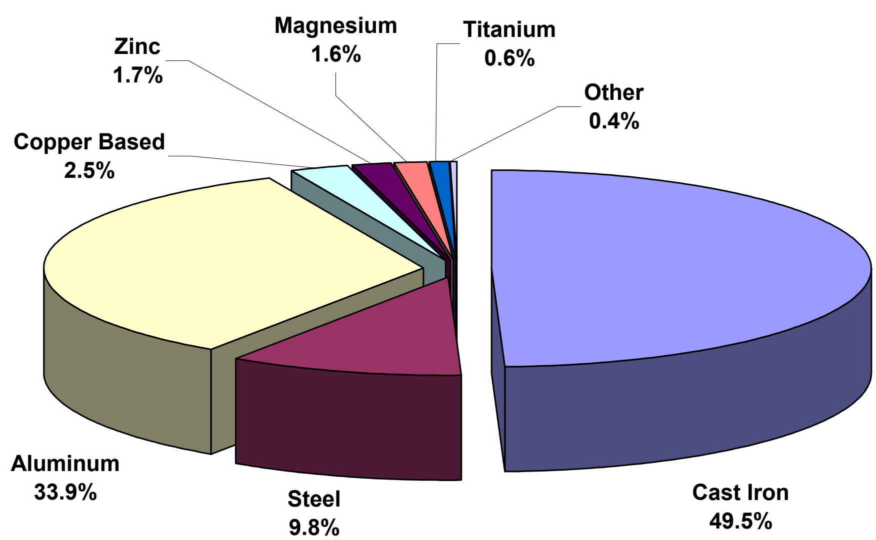
	Tacit Energy 10^6 Btu/Ship Ton	Sales $ per Ship Ton	Tacit kWh per Ship Ton	kWh/$ Sales	Energy Cost $ per Ton Sales	Energy Cost per $ Sales
Gray Iron	29.7	986	8,767	8.89	140.69	14%
Ductile (Other than pipe)	26.0	1,494	7,689	5.15	117.67	8%
Ductile Iron Pipe	7.8	1,020	2,284	2.24	46.26	5%
Steel	36.5	2,976	10,722	3.60	178.15	6%
Al High Pressure Die Casting	60.6	3,800	17,799	4.68	296.49	8%
Al Permanent Mold/Sand	99.4	5,000	28,829	5.77	555.81	11%
Al Lost Foam	81.9	5,500	24,062	4.37	399.61	7%
Mg Die Casting	67.8	6,300	20,146	3.20	297.26	5%
Zinc Die Casting	23.4	2,200	6,901	3.14	120.88	5%
Copper-Base; Sand	37.3	4,150	11,089	2.67	165.57	4%

Note: Estimated 2003 energy costs: Coke = $180/Ton, Electricity = $ 0.04475/kWh, Natural Gas = $ 6.63/Mcf (EIA, DOE 2003(36))

*Energy data from "DOE U.S. Metalcasting Energy Profile(2), Casting Sales from "2003 AFS Metalcasting Forecast and Trends"(1).

Table 10 also segregates iron and aluminum alloys into different casting processes, each with different specific energy profiles. These areas are discussed further in succeeding chapters. The actual tacit energy profile of the casting industry is shown in Figure 1.

Figure 1 - Estimated 2003 Metalcasting Tacit Energy Usage*

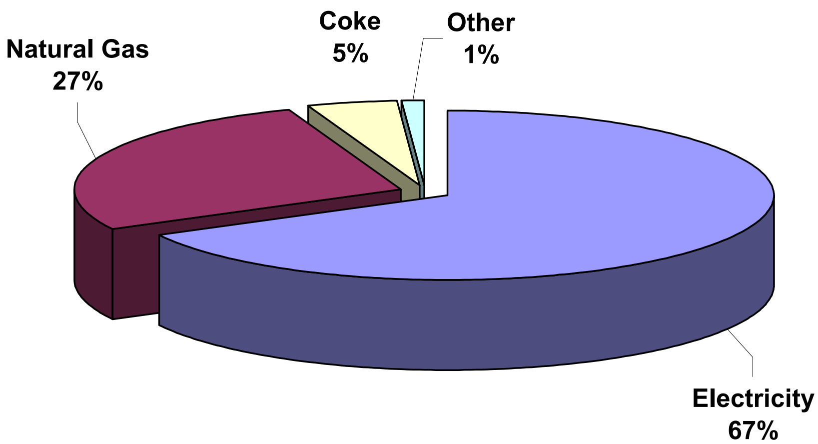


***Data from Appendix A.**

Figure 1 indicates a shift from the information given in Table 6, whereby it was shown that cast iron comprises 68 percent and aluminum makes up 16 percent of industry casting shipments. Iron castings represent 68 percent of casting shipments and consume 49.5 percent of casting sector energy. While aluminum castings are only 16 percent of cast tons shipped, they consume 33.9 percent of the energy consumed by the entire casting sector.

This is particularly significant considering the overall trend toward increased aluminum casting shipments. Steel castings are 9 percent of the shipments and about 9.8 percent of the energy usage per ton. Other casting types have limited information available on energy usage; however, they are also much smaller energy consumers.

Figure 2- Estimated 2003 Metalcasting Tacit Energy Use By Type*



*Calculated from data listed in Appendix A.

The type of energy used by the casting industry is shown in Figure 2. Much of the natural gas consumed is used by aluminum facilities, which primarily use natural gas melting and holding furnaces. The coke and much of the electricity consumed is for cupola and induction-melt cast iron production and steel production using only electric melting.

Many studies have focused on which specific processes within casting facilities use the most energy. The lack of accurate, process specific, energy usage data makes it very difficult to determine, with any degree of accuracy, the differences in the energy usage between the many foundry processes, such as molding or casting machine types. Frequently the differences in machine uptime or the type of castings produced are more significant than the differences in the process-specific casting methods. There are, however, certain conclusions that can be drawn regarding the general energy consumption of the casting industry as a whole. Table 11 summarizes data from the results of literature searches where estimates were made concerning process-specific energy consumption trends. The table represents energy consumed on-site, not the tacit energy. In all cases, the primary process area that consumes the most energy is melting or melting and holding furnaces of all types, consuming between 50 percent and 70 percent of facility use. When tacit energy is considered the melting and holding furnace areas become more significant at an estimated 72 percent.

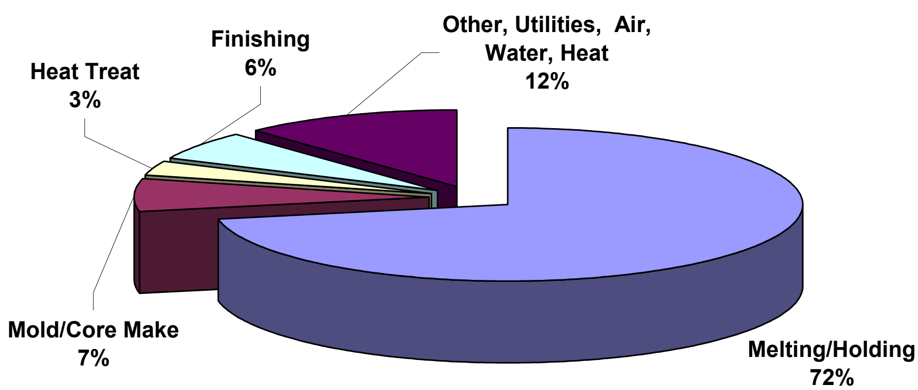
Table 11 - Survey of Delivered Energy Usage by Metalcasting Process Areas

Study	Melt & Hold	Mold or Mold/Core	Core	Heat Treat	Clean	General
Foundry Energy Management, 1990 (9)	64%	3%	3%		9%	21%
Large Auto, (Gray and Ductile Iron) 2001*	50%	15%	7%		9%	19%
Department of Energy/Cast Metal Coalition (All alloys)	58%					
Energy Conservation in Steel Foundry, PMI AFS 92-01	60%			23%		17%
Energy Conservation in Iron Foundries, India 2000 (16)	70%	15%				15%
Energy and Environmental Profile of the U.S. Metalcasting Industry 2002 (4)	55%	12%	8%	6%	7%	12%
Energy Profile and Reduction of Specific Consumption of Energy in the Foundry(15)	58%					

* General was estimated and Mold/Core includes line holding furnaces.

Figure 3 gives an estimate of the process-specific energy profile of the metalcasting industry based on tacit energy. Heat treat is significant to those facilities that are heat-treating castings, such as certain steel alloys and ductile iron pipe, but taken as a whole it is a small percentage of the total metalcasting industry profile. Melting and holding stands out above all other process areas with an estimated 72 percent of the metalcasting industry tacit energy consumption. Figure 3 was calculated by converting **delivered energy** data, obtained from published energy reports, to **tacit energy**.(4) Aluminum metalcasting energy use was also updated with information provided from recent Department of Energy metalcasting initiatives.(2) Table 11 confirms the general assumptions used to develop the profile shown in Figure 3.

Figure 3 - Typical Metalcasting Tacit Energy Profile by Process*



***Estimates from Table 11 and Appendix A. (2)(4)**

An analysis of energy usage in the metalcasting industry dictates that energy usage in the melting and holding areas must be reviewed in detail. Reductions in these areas are vital to making significant reductions in the metalcasting industry's overall energy usage. An examination of heat treat operations is needed in the metal alloy sectors.

CHAPTER 1. MELTING

Section 1 of Chapter 1 covers the theoretical minimum energy required to melt one ton of metal by alloy type. This analysis determined the energy required to melt metal without any consideration for conversion efficiencies or yield considerations. This section also gives the theoretical energy calculations to raise iron and steel to heat treat temperatures. Section 2 covers the identified best practices and industry averages used by the industry today in melting metal. The best practice is derived from actual metalcasting facility data, where available, or supplier data, absent facility data. Best practice represents the best performance actually being achieved in operating metalcasting facilities. The industry average is considered the average energy being consumed by metalcasting facilities to melt one ton of iron. Section 3 covers the specific energy improvements identified in Sections 1 and 2, and converts these improvements into energy and CO_2 reductions.

SECTION 1. THEORETICAL MINIMUM

Section 1 covers the theoretical minimum energy requirements to melt one ton of metal. The energy calculations are performed by determining the theoretical total energy content (enthalpy) of metal at typical tapping temperatures and subtracting the total energy at ambient temperatures to determine the energy requirements to melt metal in a casting facility. This energy difference, or melting energy requirement, is shown in Table 12. The enthalpy of metal is considered zero at 77°F. The energy levels for steel are also shown for other temperatures to allow the analysis of the requirements to heat treat steel at temperatures lower than tapping temperatures.

Table 12 - Theoretical Cast Alloy Energy Requirements (kWh/ton)*

Temp °F	SAE 1040 Mild Steel	Gray Cast Iron	Ferritic Ductile Iron	Pearlitic Ductile Iron	A-357 Aluminum	Magnesium	ASTM 903B86 Zinc	ASTM B22-A Bronze**	ASTM B146-6A Yellow 2 Brass**
77	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200	8.2								
800							72.1		
1000	72.3								
1400					285.3	313.1			
1750	162.7		170.2	170.0					
2250								137.2	177.0
2750		351.5	351.5	351.5					
3000	358.6								

*All values in reference to a standard state of zero energy at 77°F.
** Copper-based Alloys
Theoretical Energy Requirements, Technikon (28)

The values in Table 12 are enthalpy values for several representative alloys at the specified temperatures and states. The values represent the theoretic energy requirements to achieve the temperatures necessary to perform specific processes on the materials listed. The listed values are the "sensible heat" – the real world heat that flows from one place to another. Enthalpy, defined as the internal energy plus pressure times the volume, is the closest thing to sensible heat that thermodynamics can provide when the difference in enthalpy for two conditions is determined. These values represent the proportional heat content of each component element raised to the temperature of interest plus any phase or structural changes that the material may have passed through on the way. The values do not include any energy adjustment for the solution of the alloying elements in the base metal solvent, or further interaction between alloying elements.

Table 12 is further refined in Table 13 to depict the energy content of the alloys on a Btu per pound and Btu per ton basis for tapping and typical heat treat temperatures. The aluminum type listed in Table 13 is the one that most closely approximates the average energy content of the alloys used by the North American Die Casting Association (NADCA) in its "Energy Savings Manual." (12)

Table 13 - Theoretical Energy Requirements by Metal Type*

	1000°F	1750°F	Tapping Temperatures							
	Steel	Steel	Steel	Gray Iron	Ductile	Aluminum	Magnesium	Zinc	Bronze	Brass
Btu/pound	123.5	277.8	612	600	600	493	535	123	234	302
10^6 Btu/Ton	0.247	0.556	1.225	1.200	1.200	0.986	1.070	0.246	0.469	0.604

*Aluminum factor of 493 Btu per pound chosen per NADCA estimates as average Al alloy.
Theoretical Energy Requirements, Technikon (28)

Because energy appears in several forms and the nature of matter is so diverse, the energy accounting is done to standard references instead of absolute values. The energies involved in physical and chemical processing are those associated with the electron configuration of the atom; more specifically, those of the chemical bonding electrons in the outer shells of each atom. The first standard is to base thermodynamic values on a standard number of atoms, Avogadro's number of atoms ($6.023\ 10^{23}$ atoms). That quantity defines the chemical term "mole" (molecular weight).

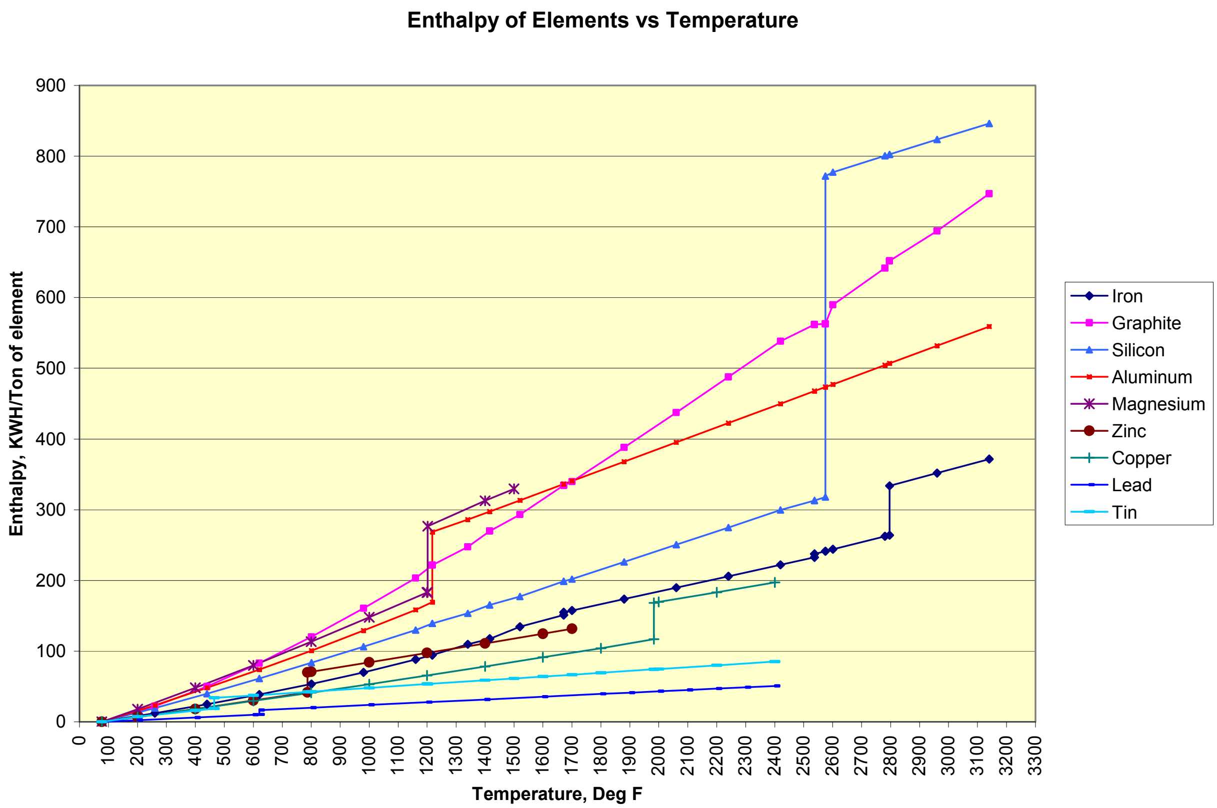
The mole is expressed in terms of the measurement system being used. In scientific circles, the mole is defined as the weight of the element or molecule expressed in grams (gram molecular weight). In engineering circles, the mole is usually expressed in pounds (pound molecular weight). The energy contained in a pound mole is greater than the energy contained in a gram mole in proportion to the mass represented by a pound of material versus a gram of the same material. In the thermodynamic bookkeeping system, this problem is solved by using larger energy units for pound moles (lb-calories/lb-mole) than for gram moles (gm-calories/gm-mole) so that they have the same numerical value.

In processing, it is customary to express composition as a weight percent of the component to the total amount of material. Different materials have different molecular weights; therefore, proportions based on weight do not conveniently represent the number of thermodynamic units (moles) present. In thermodynamic calculations the composition is usually expressed as "mole fraction," the fractional number of moles of one component relative to the total of one mole. Conversion from one system to the other requires inclusion of the elemental or molecular weights of the components.

The energies associated with metal alloys do not combine simply as sums of their components throughout the entire compositional spectrum. The simple combination of energies is known as Raoult's law. Raoult's law is followed for very dilute solutions of alloys. When the ideality of Raoult's law is not an accurate representation of the real data, but the data are nearly linear over a limited range, a tangent to the real data curve is used and known as Henry's law. Henry's law is followed in dilute solutions of alloying up to approximately 10 percent solute in the solvent metal. Compositions whose energy combinations are not represented by either Raoult's law or Henry's law must be determined by other more complex thermodynamic calculations, graphical interpretations, or by empiricism. In this report, the determinations are based on Raoult's law. Comparisons to other reference data support this as a reasonable choice.

Figure 4 gives a graphical representation of the enthalpies of different metals at varying temperature levels.

Figure 4 Enthalpy vs. Temperature (Technikon, 2003(28))

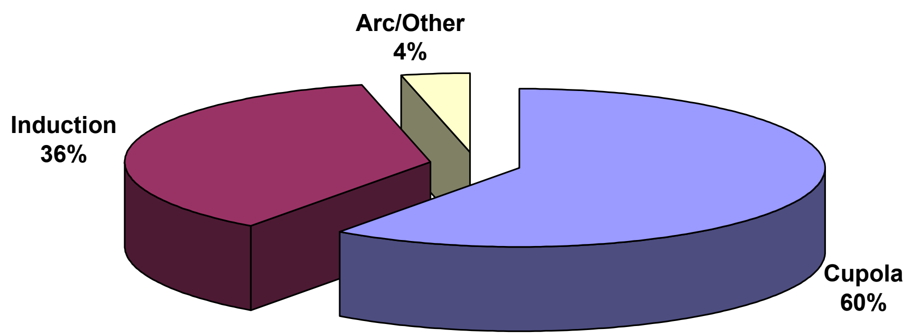


SECTION 2 – BEST PRACTICE

IRON CASTINGS – MELTING

Iron casting production represents 68 percent of the metalcasting production tons shipped and consumes 49.5 percent of the energy. The melting methods utilized by iron metalcasting facilities are primarily cupola and induction furnace melting. Induction furnaces (EIF), and to some extent resistance heating, are also used for holding furnaces between melting and casting lines to smooth out metallurgical variations and for temperature control or superheating metal after melt. There are also several arc melting furnaces (EAF) in use by iron facilities, but these are not discussed in this report due to the small number utilized by iron facilities.

Figure 5 - Cast Iron Melt Tons by Furnace Type*



***Energy and Environmental Profile 2003 (4)**

A profile of the iron casting melting methods is shown on Figure 5. The information for Figure 5 was taken from a background document published by the U.S. Environmental Protection Agency in December 2002 for regulatory purposes.(5) This study also indicated that 95 percent of the induction-melting furnaces in the United States were under 10 tons per hour melt capacity. The cupola melt facilities are typically larger casting facilities and pipe shops. The higher initial facility costs associated with cupola installations discourages their use by smaller facilities. The cupola melting method also requires more highly trained operating personal to ensure quality castings. The cupola melting method changes the chemistry of the metal by adding carbon to iron melted in the cupola. This carbon pick up and other alloying mechanisms allow the cupola to melt a wide variety of ferrous scrap materials. The induction melting process primarily melts scrap iron and does not change the chemistry of the metal melted. Induction melting requires that carbon and other alloys be added to the furnace to ensure appropriate chemistries. The decision on what melting method to use is based on production volumes, ferrous scrap availability, and technical expertise available in the melt department. At higher melt rates, the inherent lower cost per ton operating costs of the cupola

– utilizing coke as a primary fuel source – outweighs the higher capital and maintenance costs associated with the cupola operation and its accompanying support facilities. A cupola can also utilize a wider variety of lower cost ferrous scrap than is suited to induction melting. Induction melting, however, has the advantage of being able to quickly switch between different ferrous alloys and to allow metallurgical analysis to be performed and chemistries adjusted prior to removing iron from the induction-melting furnace.

The decision on what melting method to use is therefore not a clear choice, but one based on production volumes, alloy types, energy costs, ferrous scrap availability, and technical support staff. This report discusses both methods and makes recommendations on how to utilize each melting method more efficiently.

Facility energy profiles, provided in Appendix A, show that the induction furnace facilities analyzed for this study had an average tacit energy consumption of 43.05 10^6 Btu per ton of gray iron castings shipped, while the average gray iron cupola shop was 16.31 10^6 Btu per ton shipped. This comparison is certainly more complicated than just looking at melting methods. The types of castings produced, core content, casting yield, as well as the use of holding furnaces and different casting processing all affect the overall energy usage. The gray iron cupola shops analyzed varied from a low of 9.98 10^6 Btu per ton to a high of 20.55 10^6 Btu per ton for an automotive casting facility. The ductile iron induction furnace-melt shops listed had energy usage similar to gray iron cupola shops, while the ductile iron pipe cupola shops had the lowest tacit energy consumption of 7.84 10^6 Btu per ton. The metallurgical and process differences associated with different metals and casting types are factors that must be understood more fully and are discussed in Chapter 3, Section 1 as well as Chapter 2, Section 2, where casting scrap and yield are discussed.

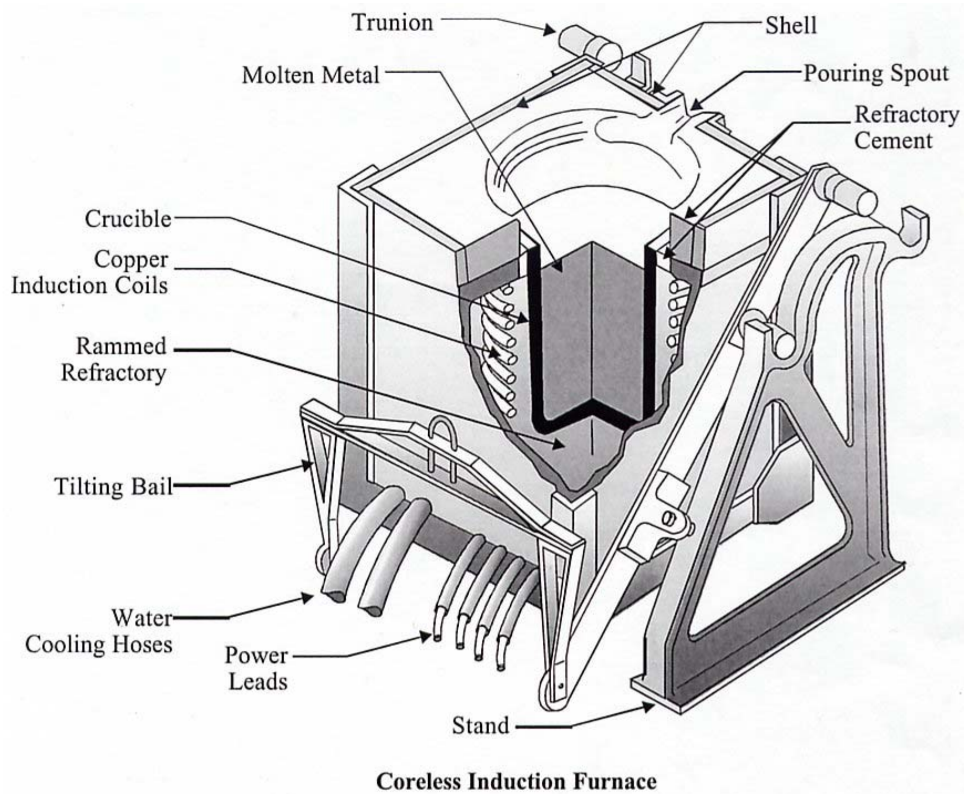
A cupola melting operation also tends to be more of a continuous process, because stopping a cupola for extended periods of time will result in metallurgical problems with the iron, which remains in the cupola. An induction-melting furnace can hold iron for an indefinite period of time, acting like a holding furnace. This ability to hold iron may encourage or allow induction-melt shops to maintain additional induction-melting furnaces online, rather than running fewer melting furnaces at higher utilization levels. This practice is very energy intensive. The induction-melt furnace shops, as previously mentioned, are also smaller foundry operations in contrast to the larger cupola melt shops.

An exact analysis of all the energy associated with different melting types is difficult to isolate from the total energy use data, except to indicate that the tacit energy usage is generally higher with similar iron types for induction melting. The melting units are reviewed individually in this section to determine their best practice energy usage compared to the theoretical minimum usage and industry averages.

Induction Furnaces

In a coreless induction furnace, a water-cooled, helical copper coil surrounds a refractory-lined cavity containing the charge material, as shown in Figure 6. An induced current is produced in the charge material by an alternating current in the coil. Once the charge is molten, stirring action occurs as a result of the interaction of currents in the melt with the magnetic field. Stirring velocity increases at higher power and lower frequencies.

Figure 6. Coreless Induction Furnace



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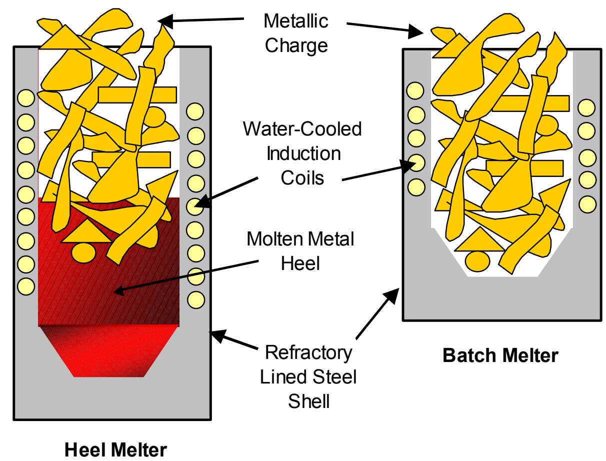
Electric induction furnaces first utilized for melting purposes were primarily "heel" style furnaces utilizing line frequency power supplies. The control technology available in the 1950s did not allow for variable frequency power supplies, requiring induction-melting furnaces to run at 60-Hertz line frequency. This limited furnace designs to larger coreless melt furnaces with low power densities. Power density is the power rating of a furnace in kW/ton of furnace capacity, which typically runs 200 to 250 kW/ton. Furnace designs must also take into consideration the mixing of iron in the furnace to ensure a homogenous mixture without excessive stirring. The medium to large capacity melt furnaces were also primarily heel melters, meaning that they maintained a heel of iron in the furnace at all times, requiring holding power when not melting. The iron maintained in the heel was typically 60 to 80 percent of the furnace capacity. The energy losses associated with holding iron between melts, as well as the larger overall furnace sizes resulted in high overall energy consumption rates. The basic design differences between the heel melt and batch melt induction furnaces are shown in Figure 7.

The older power supplies were also very inefficient, with losses approaching 40 percent. The heel was used primarily to help reduce stirring associated with line frequency melting, but also required that charges be preheated to ensure that no wet charges were put into the molten iron in the furnace heel.

Figure 7. Induction Melting Furnace Types



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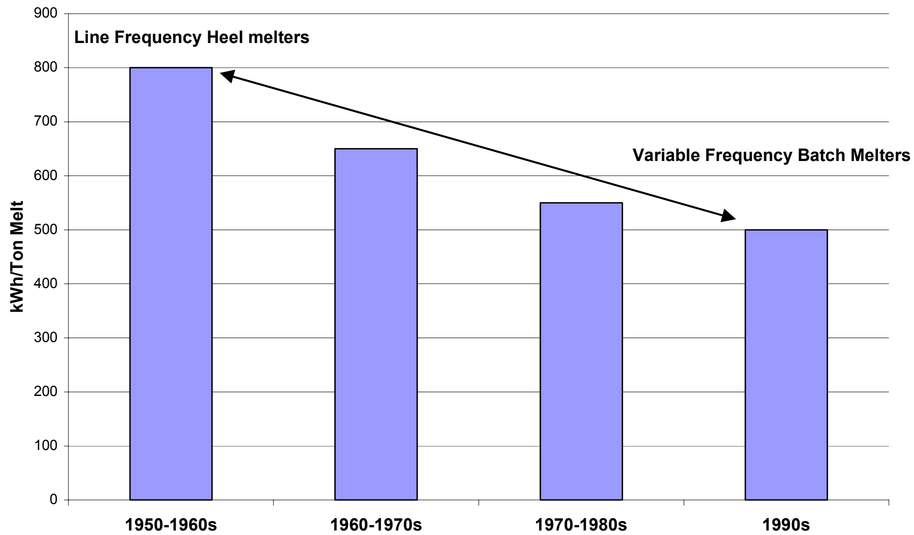
As more sophisticated solid-state power supplies with increasingly higher power ratings became available, the "batch" furnace increased in numbers. A batch-melting furnace empties the furnace after each melt cycle, reducing the holding power requirements. Over time, methods were developed to increase the frequency of the power supplies, allowing for increased power densities and smaller furnace sizes. Advancements in solid-state power supplies, as well as computer controls, allowed engineers to develop infinitely variable frequency and voltage power supplies during the 1990s. These new designs allow the maximum utilization of furnace power throughout the melting cycle, with good control of stirring. Small furnaces with very high power densities of 700 to 1,000 kW/ton can now melt a cold charge in 30 to 35 minutes. Since the metallic charge is not immersed in a bath of iron, no preheating of the charge is required, but is still sometimes used. Preheating can help increase furnace melt rates at the expense of energy efficiency.

Another inherent advantage of the batch induction melter is that when melting a magnetic charge such as solid scrap iron, the coil efficiency can be as high as 95 percent, compared to 80 percent when heating the molten bath in a heel melter. **Hysteresis losses** associated with induction heating of a solid ferrous material are responsible for this increased coil efficiency during the first part of the melting cycle.

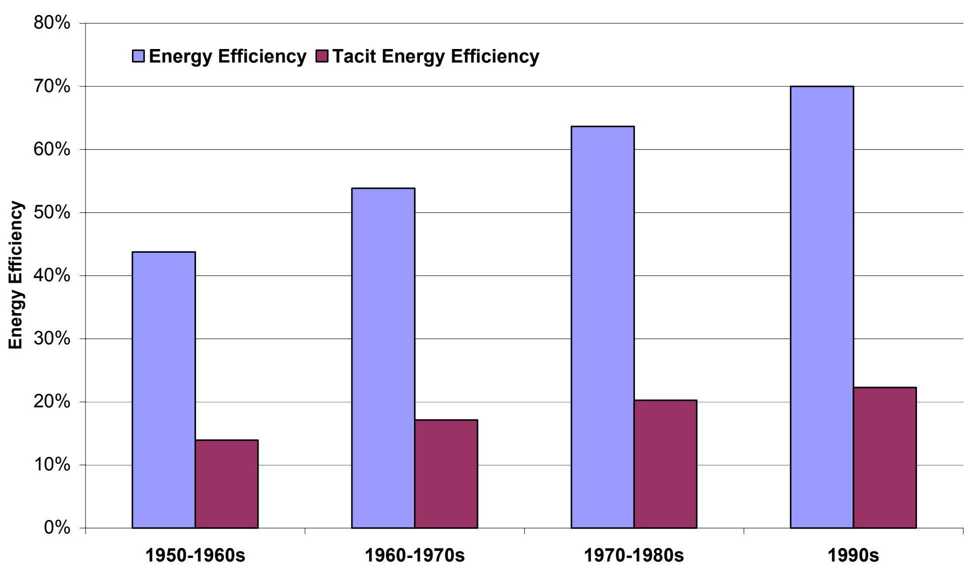
Figure 8 shows the reductions of energy requirements for induction melting from the 1950s to the present time. Estimates of typical melting energy requirements have been reduced from an estimated 800 kWh/ton in the 1950s to 500 kWh/ton for current technologies. This chart depicts delivered power to show differences in furnace design considerations.

Figure 8 - Historical Induction Melting Furnace Energy* (Delivered)



* Data from Inductotherm Publications (19)(20)

Figure 9 - Iron Induction Melting Energy Efficiency, Delivered and Tacit*



* Data from Inductotherm Publications (19)(20)

Figure 9 converts the improvements in induction furnace designs to energy efficiency. The overall efficiency with which power is utilized within the melting process has increased from 44 percent to 70 percent between the 1950s and the 1990s. Furthermore, current power supply efficiencies exceed 96 percent on larger furnaces; thus, induction-melting efficiency is not likely to increase significantly.

Tacit energy efficiencies increased from 14 percent to 22 percent during the same period. The tacit energy efficiency is also shown in Figure 9 and takes into consideration power plant efficiency, as well as transmission losses.

Figure 10 shows an energy balance of the modern induction furnace batch melter. The chart shows that with 1.81 10^6 Btu delivered to a foundry, 1.16 10^6 Btu are actually used to melt each ton of iron. The energy used by a power plant to provide this energy to the foundry is 5.7 10^6 Btu. This figure is based on a best practice batch induction melting foundry averaging 530 kWh/ton melt. The calculations shown are for melt energy only and do not consider holding furnaces. This analysis does not consider cooling water pumps or heat exchangers because the differences between melting technologies would be insignificant.

A comparison was performed to show the differences between older heel melters and modern batch melting induction furnaces. The example shown in Figure 10 is considered the "best practice" batch melter. The total energy data was obtained from a best practice iron foundry and the breakdown of energy losses was taken from literature published by Inductotherm. (19)(20).

Figure 10 - Modern Induction Melting Process Energy Balance (10^6 Btu/Ton Melt)*

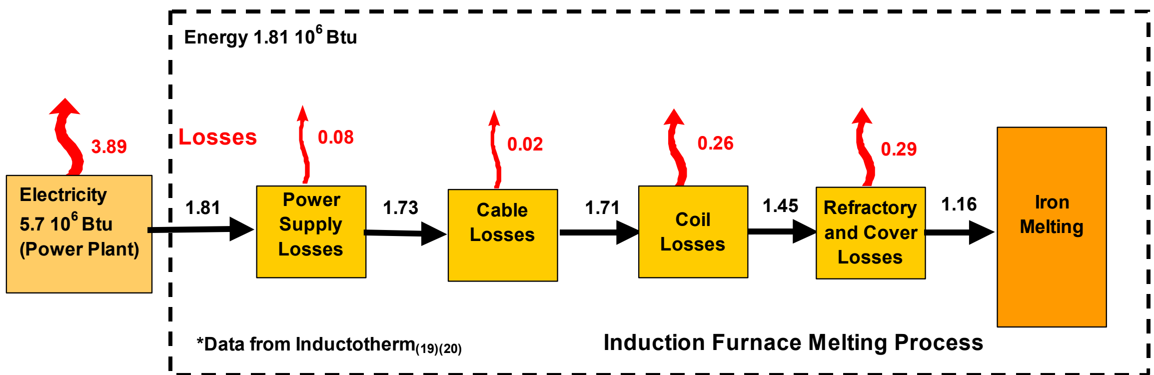


Table 14 is an estimate of the actual performance of a well-run heel melter compared to a well-run batch melter. It is assumed for this analysis of only the technology differences in induction melting that in both cases the furnaces are running at maximum production for 16 hours per day. The heel melter is considered running 16 hours per day and held overnight with power on the melt furnace. (The effects of scheduling on melting efficiency are not considered.)

The older heel melter is estimated to run at 800kWh per ton furnace power, with 20 percent holding power on the 8 hour down shift per day. The heel melter also requires that the charge material be preheated prior to placing it into the melt furnace, and therefore the natural gas-fired preheater was considered in the energy usage for the "estimated" heel melter energy requirement of 954 kWh per ton. The batch melter "estimated" energy usage of 530 kWh per ton was based on information received from a well-run best practice foundry. The energy use is converted to tacit energy for comparative purposes.

Table 14 - Estimated Iron Induction Melting Energy Usage							
	Per ton Melt						Per Ship Ton
Item	Gross kWh/Ton	Melt Loss	kWh/Ton	Tacit kWh/Ton	10^6 Btu/Ton	Tacit 10^6Btu/Ton	Tacit 10^6Btu/Ton**
Heel Melting Calculated	800	1.5%	812	2550	2.77	8.71	14.52
Heel Melting and Holding Estimated*	954	1.5%	969	3041	3.31	**10.39**	**17.31**
Modern Batch Melter Calculated	500	1.5%	508	1594	1.73	5.44	9.07
Batch Melter and Holding Estimated	530	1.5%	538	1690	1.84	**5.77**	**9.62**

*Includes hold power for 8 hours per day and preheat gas at 74 kWh/ton melt for heel melter.
**Ship tons consider 60% yield.

Table 14 indicates that a well run heel melter uses 10.39 10^6 tacit Btu per ton of iron melted, while a modern well run batch melter uses only 5.77 10^6 tacit Btu per ton for a savings of 45 percent in melting energy usage.

The result of applying these savings to the entire industry for 2003 production levels is shown in Table 15. Table 9 gave a breakdown of iron casting production as gray iron, ductile iron, and ductile iron pipe. Estimates of induction furnaces utilized by the industry are shown in Figure 5. Industry experts and suppliers interviewed for this study estimated that heel melters comprise 60 percent of the ductile iron and gray iron induction furnaces used by the industry. Table 15 uses this assessment to estimate the tacit energy currently used by all induction melting furnaces in the iron casting industry. Again, this is only for the melting furnaces themselves, and assumes they are properly scheduled.

Table 15 - Best Practice Induction Melting Energy Reductions			
Item	Estimated 10^6 Btu/Ship Ton	Estimated Ship Tons	Tacit 10^{12} Btu
Heel Melting Furnaces (60%)	17.31	2,050,690	35.50
Batch Melting Furnaces (40%)	9.62	1,367,127	13.15
Average	14.23		
Total Estimated Energy			48.64
Batch Melting Furnaces (100%)	9.62	3,417,817	32.87
Difference per Year			**15.78**

The tons melted are calculated by taking the tons shipped from Table 9 and applying a 65 percent yield factor. This analysis shows that replacing all heel melting furnaces with modern batch melters would result in saving 15.78 tacit 10^{12} Btu per year at 2003 estimated production levels.

RECOMMENDATIONS – IRON INDUCTION

The documents reviewed and interviews conducted to obtain information for this study also yielded some work practice recommendations, which would assist foundries in reducing energy consumption. The following are some of these recommendations concerning induction-melting processes:

1) Streamline temperature measurement – automated furnace temperature and power controls prevent overshooting temperature settings.
2) Reduce the time the lid is open for all purposes while melting or holding iron. A 12-ton capacity furnace (storage tons) loses 14 kWh for each minute the lid is open.
3) Power leads – flexible power leads should be as short as practical, and configured in a "diamond" type configuration.

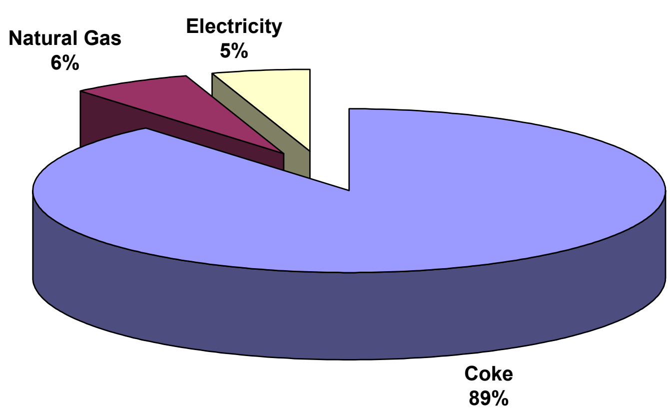
Cupola Melting Furnaces

A cupola melting furnace is a vertical shaft furnace that uses either a refractory-lined, or bare-steel shell. The bare-steel shell design uses water cooling on the outside of the bare shell, and is referred to as a water walled-cupola. Air is fed into the cupola for the combustion of coke through openings or protrusions in the steel shell, called tuyeres. The coke combustion air is usually heated in a "hot blast" cupola, but can be ambient air and is then referred to as a "cold blast" cupola. The main energy source for melting in a cupola is coke and, to a lesser degree, the energy of the hot blast, as shown in Figure 11. The electricity used by the cupola is primarily for the cupola hot blast and emission control fans. A diagram of the two types of cupola designs is shown in Figure 12.

The conversion of coal into coke is a relatively efficient process, since little of its original Btu value is lost in the coking ovens. The coking ovens heat coal in a reducing environment, driving out volatiles, which are then used to fuel the coking ovens. Coke is then consumed in the cupola, applying this form of energy directly to its intended use of melting iron. This process minimizes conversion and transmission losses present in other forms of delivered energy such as electricity. Coke and coal Btu values vary by source; however, for this analysis the heat value of coke is considered 13,000 Btu/pound, with a tacit energy value of 14,000 Btu/pound.

The cupola melting process maintains a "bed" of hot coke in the lower portion of the vertical shaft. The coke bed is maintained by the creation of a reducing environment, which does not rapidly consume the coke at the bottom of the cupola. The area in front of the tuyeres, called the "oxidation zone," is primarily where coke is consumed to provide the energy to produce molten iron. To maintain this coke bed, the reducing environment is high in carbon monoxide. As hot gases pass up through the vertical shaft, the ferrous materials "charged" into the top of the shaft are heated and melt. The carbon monoxide and carbon dioxide formed when coke is consumed reach a balance, depending on the specific operating conditions set up by the cupola operator. The coke as fuel, ferrous scrap, alloy additions, and limestone as flux, are all "charged" in layers into the top of the vertical shaft and gradually work their way down the shaft as iron is melted and coke is consumed. The limestone as flux cleans the iron and runs out the bottom of the cupola as "slag."

Figure 11 - Cupola Energy Sources by Type (Tacit Energy)*



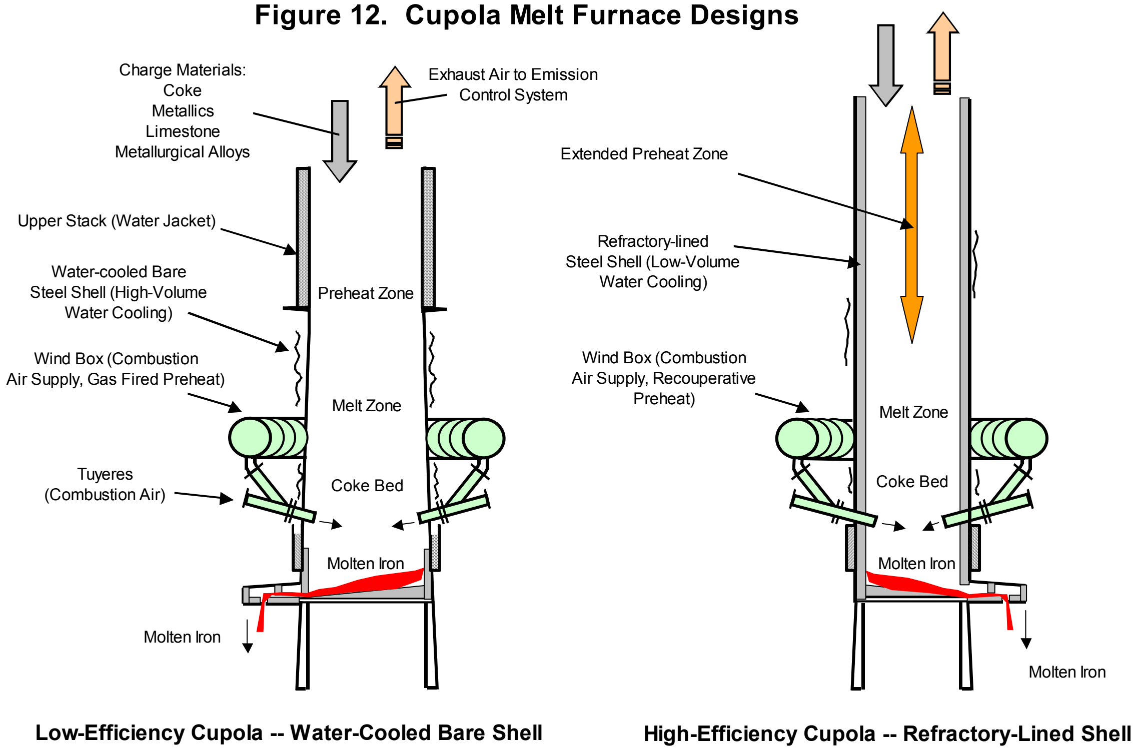
*Data from Kuttner-Modern

The cupola operating parameters, controlled by the cupola operator, can vary the height of the coke bed and thereby change the carbon pick up and other metallurgical properties of the iron. In this way, both the metallic charge make up, and alloys added, as well as the operating parameter of the cupola affect the metallurgical properties of the molten iron produced. This is an overly simplified description of the cupola melting operation, but it should suffice for the following energy use discussions.

The cupola has the advantages of being able to change the metallurgical properties of iron, as well as use coke as fuel. It can also melt many different forms of ferrous scrap not suited for induction furnace melting operations. The reducing environment, however, results in high carbon monoxide content in the stack gases passing up through the charge materials. This high carbon monoxide content and, to a lesser extent, the temperature of the stack gases is energy lost as the stack gases are exhausted from the upper stack. This waste gas stream also contains small amounts of hydrogen and other volatile organics from the coke and certain types of ferrous scrap. The carbon monoxide generated is not the result of a poor combustion process, but a characteristic of a properly running cupola. The exhaust gases leaving the top of the cupola have a high particulate loading, and therefore add-on pollution control equipment is required. Modern day cupolas also burn the carbon monoxide and volatiles in afterburners, which are usually required by local environmental regulations.

Cupola designs have changed dramatically during the past 40 years. During the 1960s, cupolas used refractory-lined shells with no water cooling, and heated blast air was only beginning to be applied to cupola melting installations. The problem with this design was that the cupola melting campaign was limited to about 16 hours. This was due to the limited refractory life of the brick used to line the cupola shells. It was typical to use two cupolas, side-by-side, to supply iron to foundry lines 16 hours each day. Then, to fill the need to run longer production campaigns, water-walled cupolas were developed that could run for more than two weeks continuously without major repairs. This design used a high volume of water on the outside of the steel shell without a refractory lining. The cooling effect of the water on the bare shell required additional energy to be supplied by coke in the charge; however, the savings inherent in running long campaign cupolas far outweighed the additional cost of coke.

Figure 12. Cupola Melt Furnace Designs



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As energy became more expensive, foundries and suppliers found ways to design refractory-lined cupolas that were also capable of long production runs between major repairs. The newer designs usually use a small volume of water on the outside of the shell in addition to the refractory lining. This water allowed the refractory materials in the melt zone to burn out until it felt the cooling effect of the water-cooled shell. This change improved the energy efficiency of the water-cooled, refractory-lined cupolas to near the level of the older refractory-lined shells. Both cupola designs are shown in Figure 12.

Another major change in cupola design was the advent of computer modeling applied to cupola melting processes. The trial and error methods used in past years has been replaced with computer simulations starting in the 1980s. These models allowed engineers to develop an ideal cupola design (physical dimensions) for a specific set of operating conditions or ferrous scrap material type. Cupola design specifications cannot be easily changed; therefore, at other than design operating conditions they lose operating efficiency. Design parameters, which include production rates, dictate ideal design specifications such as the cupola shell diameter, stock height (height of the charge above the tuyeres), tuyere sizes, and blast volumes.

All of these issues affect energy losses. A proper diameter shell and stock height ensures that the exhaust air effectively preheats the cold charge materials before reaching the melt zone, thereby reducing coke usage. Higher production rates can be achieved by changing charge materials and/or using pure oxygen in the cupola to supplement the hot blast air. Most foundries use some amounts of oxygen to attain higher melt rates or as a metallurgical tool. Oxygen is used at rates of 2 to 20 percent of the blast air volumes, with most facilities using between 2 and 6 percent. The production of oxygen is itself very energy intensive; thus, this report factors the energy required to produce oxygen into the energy analysis of cupola operations. The oxygen energy shown in this report represents energy used to produce the oxygen delivered, and not energy consumed by foundries themselves.

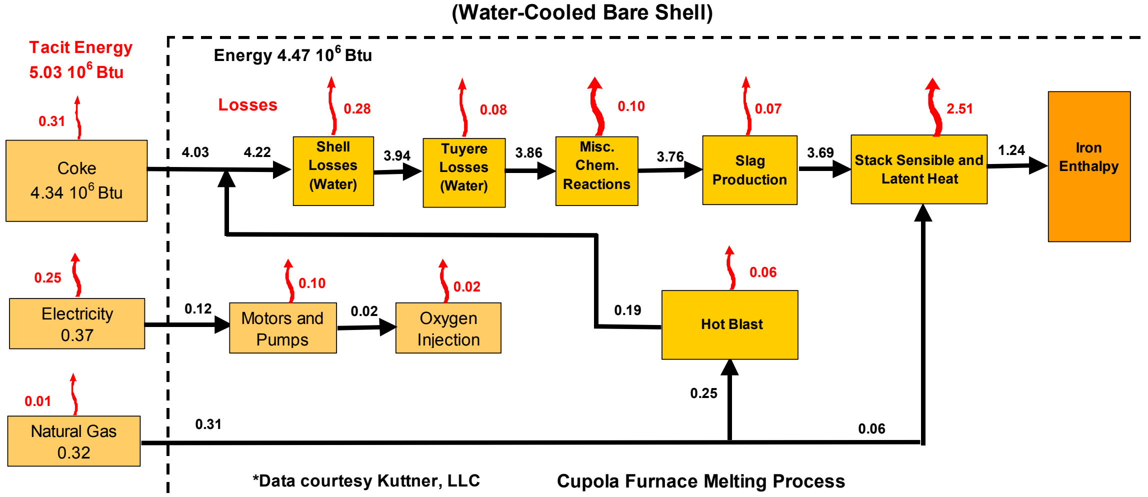
These newer cupola designs have been installed in several new cupola installations in recent years. The cost of rebuilding a cupola is quite high and as a result of this high capital cost, most cupolas have not been modified to the most energy efficient designs available.

A diagram of the energy flow into and out of a typical “low-efficiency” cupola, with a water-cooled bare shell, is shown in Figure 13. Energy input to the cupola melting process is shown with its tacit energy losses. The electric energy shown is for the hot blast blower and emission control system. The emission control is added to the melt process because no cupola can operate without this system to remove waste gases and to burn off the carbon monoxide and cool the exhaust stream. An appropriately-sized bag house blower motor was used for this example. The energy in the waste gases is shown as “Stack Sensible and Latent Heat.” The hot blast comes from a natural gas-fired unit supplying 500° F blast air to the low-efficiency cupola. The data used for calculating the energy analysis shown in Figures 13 and 14, as well as the general analysis of cupola energy efficiencies, was provided by Kuttner, LLC of Port Washington, Wisconsin.

The “high-efficiency” cupola process shown in Figure 14 has numerous differences from the low-efficiency process depicted in Figure 13. The use of a refractory-lined shell and additional stock height ensure that minimum energy is lost through the shell and that the charge is properly preheated in the upper stack. This more modern design also uses a “recuperative” hot blast unit. This type of hot blast preheater uses the heat of combusted waste gases to preheat blast air instead of using natural gas. Both the low-efficiency and high-efficiency designs use stack burners to ignite the waste gases, however, the high-efficiency design uses larger burners to assist in preheating the hot blast during start up conditions.

The energy requirements necessary to melt iron remain constant in Figure 13 and 14, however, losses are higher in Figure 13. Because coke is the primary source of energy, any additional energy losses result in increased coke usage. Increasing coke usage increases the amount of limestone added since it must “clean” the iron, and this produces more slag and results in accompanied energy losses. A comparison between these two examples is shown in Figure 15.

Figure 13 - Low-Efficiency Cupola Melting Process Energy Balance (10^6 Btu/Ton Iron Melt)*
(Water-Cooled Bare Shell)



A high-efficiency cupola design also uses the waste stack gas energy to preheat hot blast air, which is not the case in the low-efficiency design shown in Figure 13. This analysis considers the running energy associated with the cupola melting process. Table 16 summarizes a comparison of the estimated energy usage of a well-run high-efficiency and a low-efficiency cupola. This analysis assumes that the cupola is running 16 hours per day and is not held over weekends. Energy losses associated with banking cupolas overnight is estimated at 10 percent of total energy usage.

Figure 14 - High-Efficiency Cupola Melting Process Energy Balance (10^6 Btu/Ton Iron Melt)*

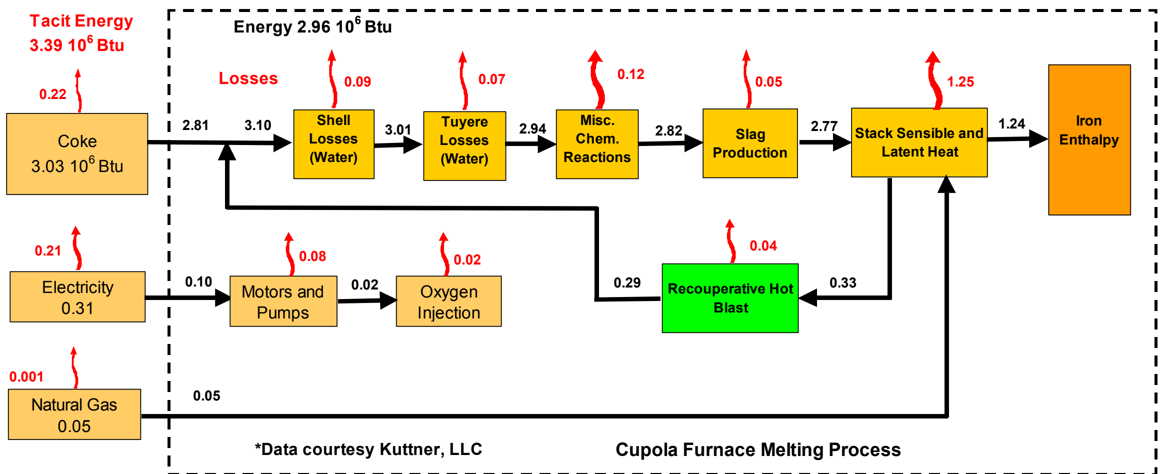
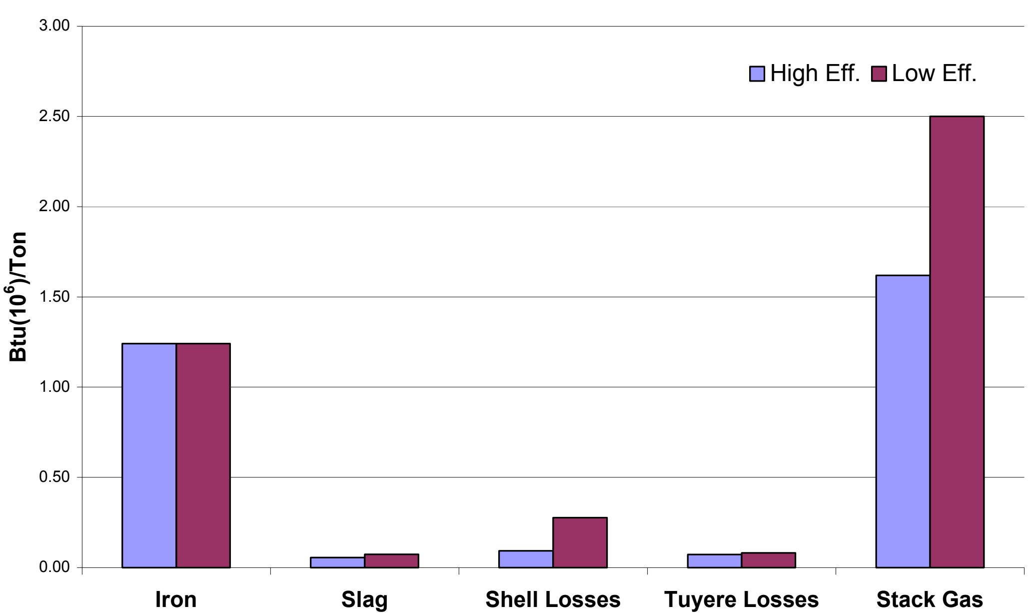


Figure 15 - Cupola Energy Outputs



Note: High Efficiency Cupola would use part of Stack Gas Losses to Heat Blast Air.

The estimated tacit energy used by a high-efficiency cupola to melt a ton of iron is calculated to be 3.84 10^6 Btu, or 6.40 10^6 Btu per ton shipped at 60 percent yield. The low-efficiency cupola would require an estimated 5.76 10^6 Btu per ton melt, or 9.60 10^6 Btu per ton shipped.

Table 16 - Estimated Iron Cupola Melting Energy Usage									
	Energy Per Melt Ton								
Item	Electrical 10^5 Btu	O_2 Equiv. 10^5 Btu***	Coke 10^5 Btu	Gas 10^5 Btu	Total Gross 10^5 Btu	Melt Loss	Total 10^5 Btu	Total Tacit 10^5Btu	Total Tacit 10^6 Btu
High-Efficiency Cupola Melting	0.77	0.18	28.10	0.51	29.57	5.0%	31.12	34.91	**3.49**
High-Efficiency Cupola Melting and Spill*	0.85	0.20	30.91	0.56	32.52	5.0%	34.23	38.40	**3.84**
Low-Efficiency Cupola Melting	1.02	0.26	40.29	3.16	44.72	5.0%	47.08	52.36	**5.24**
Low-Efficiency Cupola Melting and Spill*	1.12	0.28	44.32	3.47	49.20	5.0%	51.79	57.59	**5.76**

***"Melting and Spill" considers 10% energy losses for spill time and shutdown/start-ups.**
****Tons shipped considered 60% of melt. (Yield) *** Oxygen Equiv. Is not delivered energy.**

This analysis gives two specific examples of cupola installations that represent a wide range of operating conditions. Determining the energy savings that could be realized by all foundries using a high-efficiency cupola design is a difficult task. Several foundries are still using cold blast cupolas, however they are decreasing in numbers. Even many newer cupolas do not always utilize the most energy efficient designs, and certain older cupolas have been retrofitted for recuperative hot blasts. The high-efficiency cupola was operating at a 9.4 percent coke level and the low-efficiency cupola at 12.8 percent. The use of silicon carbide was not considered for this analysis, and if used, it should be factored into the coke usage as a fuel, depending on the carbon levels. For this analysis, because two efficiency levels were considered, it is estimated that an appropriate average energy usage estimate could be derived by considering cupola production to consist of 20 percent high-efficiency and 80 percent low-efficiency designs.

Table 17 - Best Practice Cupola Melting Energy Savings			
Item	Tacit Estimated 10^6 Btu/Ton	Estimated Ship Tons	Tacit 10^{12} Btu
High-Efficiency Cupolas (20%)	6.40	1,215,224	7.78
Low-Efficiency Cupolas (80%)	9.60	4,860,895	46.66
Average	8.96		
Total-Estimated Energy			54.44
High-Efficiency Cupolas (100%)	6.40	6,076,119	38.89
Difference per Year			**15.55**

Table 17 calculates the average cupola tacit energy consumption to melt one ton of iron at 8.96 10^6 Btu. The difference between the amount of energy used to produce the estimated 2003 cupola-melt tons and this same production using high-efficiency cupolas is approximately 15.55 10^{12} Btu.

There are other variations of cupola style furnaces such as a "cokeless cupola," which uses natural gas for energy. Several cokeless cupolas have been installed around the world but are not widely used by metalcasters. This cupola uses a water-cooled grating at the bottom of the vertical shaft, which supports a ceramic material to hold up ferrous scrap. The ceramic material is heated and the ferrous scrap melts in the upper stack above the ceramic material. This concept was originally developed by Taft in England, and further commercialized by several German cupola manufacturers. Its advantages include eliminating coke as the energy source, which facilitates much cleaner exhaust gases, and eliminating the sulfur in molten iron, which make the iron more suited for ductile iron production. Energy usage information was not available for the cokeless cupola. This method of melting requires clean charge material and also requires that carbon be added to the molten iron, depending on the type of ferrous scrap. The cokeless cupola will not superheat iron, so an external form of superheating is required.

RECOMMENDATIONS – CUPOLA MELT

Replacing cupolas and support equipment is capital-intensive. As energy prices continue to climb, this approach may be justifiable in many instances. Absent a complete replacement, certain changes or procedures can be implemented to reduce energy usage:

1) Dehumidify blast air to achieve coke savings and better metallurgical control, especially in hot humid locations. One pound of water removed will save approximately 1.2 pounds of coke.
2) Use a covered coke storage area to prevent water from being introduced into the charge. One pound of water removed will save approximately 1.2 pounds of coke.
3) Keep the upper stack full. Maximum charge levels increase preheating of metals and reduce coke usage. Varying stack levels also cause metallurgical variations; maintaining constant stack levels decreases metallurgical variations.
4) Maintain a continuous melting operation. Spill time increases energy losses and causes metallurgical variations. Consider changing the cupola lining's inside diameter and tuyere's diameter if extended levels of low – or high – melt rates are expected.
5) Replace water-walled shells with refractory-lined shells.
6) Reduce pollution control equipment horsepower requirements. (Minimize the size of charge door opening on above charge take offs or convert to below charge take off.)
7) Install inverter controlled drives on large motors, such as hot blast blower and air pollution control equipment exhaust motors, in place of dampers or waste gates (variable frequency and variable voltage). The use of these drive packages can save 50 percent of energy requirements, with reductions of 20 percent in motor speed.
8) Replace gas-fired hot blasts with recuperative hot blasts.
9) Maintain hot blasts and ductwork to ensure that maximum temperature and air volume reaches the cupola with minimum losses.

These work practice energy savings included suggestions from the "Metal Melting Efficiency Project," CCMA, Technikon, 2001. (23)

Table 18 - Induction and Cupola Melting Energy Comparison (10^6 Btu/Ton)*

	Melt Energy	Tacit Melt Energy	Tacit Ship Energy
Induction Heel Melting	3.31	10.39	17.31
Modern Induction Batch Melting	1.84	5.77	9.62
Low-Efficiency Cupola	4.92	5.76	9.60
High-Efficiency Cupola	3.25	3.84	6.40

***Data from Table 14 and 16.**

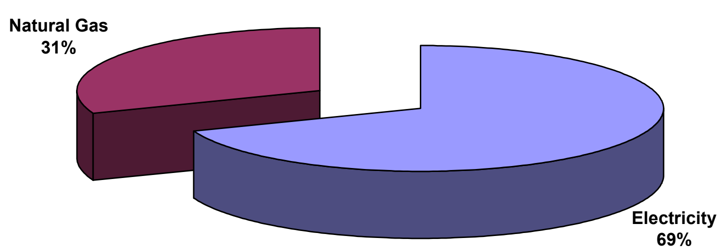
Table 18 summarizes the energy requirements of cupolas and induction furnaces. This report is not recommending one melt technology over the other. Each serves specific needs of the foundry industry. The delivered energy required to melt one ton of iron is 50 percent to 75 percent higher for a cupola melter than for an induction furnace. In terms of tacit energy, however, this difference reverses itself because of the differences in tacit energy units for electric power and coke as primary sources of energy.

STEEL CASTINGS – MELTING

The steel-casting sector comprises 9 percent of casting shipments, while using 9.8 percent of the energy consumed by the metalcasting industry. Three steel facilities took part in the "Energy Use in Select Metalcasting Facilities"(2) with tacit energy per ton shipped varying from 32.24 10^6 Btu to 97.75 10^6 Btu per ton. The study covered two low carbon steel foundries and one stainless facility. The stainless steel foundry had an abnormally high energy usage. The stainless steel shop was in the northeast with a very high heating load and employing a large number of peoples producing and processing very small castings. For these reasons, the two low carbon facilities are discussed in this report, with an average tacit energy consumption of 36.24 10^6 Btu per ton shipped using the tacit energy conversion factors covered in the introduction. Energy usage at all three facilities is shown in Appendix A. The energy used by the entire steel-casting sector is characterized by type in Figure 16.

Very little information is available on energy consumption at steel casting facilities. This analysis was developed using the limited information available from the "Energy Use in Select Metalcasting Facilities,"(2) along with general energy savings recommendations from published literature.

Figure 16 - Steel Casting Estimated 2003 Tacit Energy Use By Type*

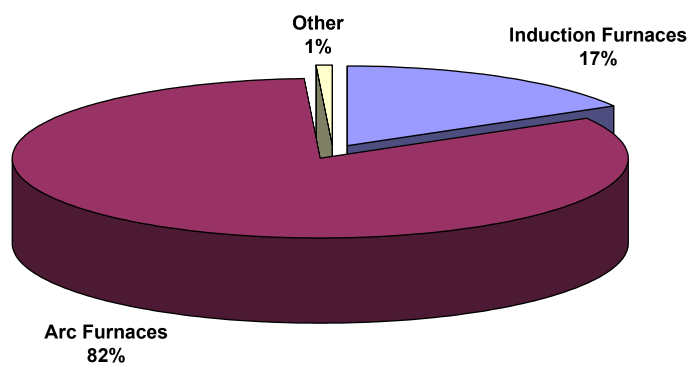


* Energy Use in Selected Metal Casting Facilities, DOE, 2003(2)

The melting of steel is performed in both arc furnaces (EAF) and induction furnaces (EIF). The arc furnace is the primary melting method and is used by 82 percent of steel foundries as shown in Figure 17.(6) Steel casting induction furnace melters are essentially the same as those previously discussed in the iron casting section of this report. Iron and steel require close to the same amount of energy to melt a ton of metal. Differences in the melt energy are due to higher tapping temperatures for steel, which varies between 2,900 and 3,100°F, while iron is typically tapped out at 2,600 to 2,750°F. The higher melting temperature for steel is principally due to the lower carbon composition.

Electric arc melting furnaces, Figure 18, consist of refractory-lined cylindrical vessel made of steel and having a bowl-shaped hearth and a domed-shaped refractory roof. Two or three electrodes are mounted vertically through the roof of the furnace and float just above the surface of the cold ferrous scrap or molten bath. Over 80 percent of arc furnaces used for steel castings are alternating current furnaces with three electrodes. Control of the electrode level above the bath is critical to the melting process efficiency. These electrodes strike an arc on the cold metal scrap or molten metal to impart energy to the bath and melt or superheat the furnace. The furnace uses a refractory-lined shell and refractory roof, but experiences significant energy losses through the surfaces of the furnace and from exposed surfaces during charging and slagging operations.

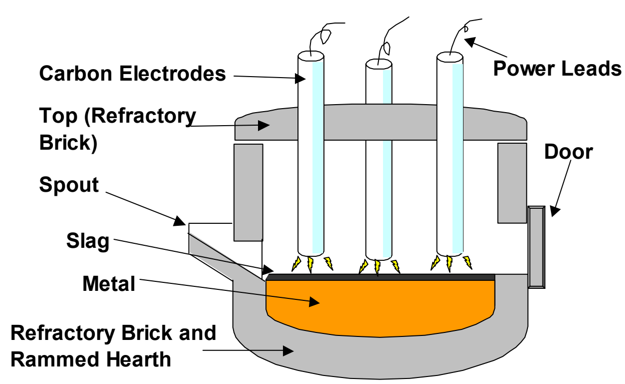
Figure 17 - Steel Melting Furnaces Production*



*Energy and Environmental Profile of the U.S. Metalcasting Industry, DOE, 1999(4)

Arc melting furnaces are the most widely used method for melting steel scrap. They can melt a wide variety of ferrous scrap materials and can accept certain levels of dirty scrap. They also use "chemical energy" to assist in the melting process and to lower the carbon levels of the molten metal. Since steel castings require low carbon level metallurgy, carbon from scrap metal feedstock and carbon electrodes must be removed from the molten metal. Injecting oxygen into the molten bath oxidizes carbon and uses the exothermic reaction to assist in melting and superheating the metal. This is referred to as supplying chemical energy to the furnace. In some instances, different forms of oxyfuels are used to provide additional energy to speed up the melting process.

Figure 18. Arc Melt Furnace



KERAMIDA, Indianapolis, IN

Arc furnaces are not good holders or efficient at superheating metal, so it is not uncommon to use induction furnaces to superheat steel after the arc melters. Induction furnaces used to melt steel require cleaner charge materials to meet metallurgical requirements, and therefore require low carbon charge to produce lower slag levels. Steel induction melting furnaces are similar to those described in

Chapter 1, Section 2, Induction Furnaces while an electric arc melting furnace is shown in Figure 18.

The two example foundry profiles documented in Appendix A, show that the induction furnace shop used tacit energy of 32.24 10^6 Btu per ton shipped and the arc furnace shop required 40.70 10^6 Btu. This is contrary to the overall analysis of the facilities, which indicated that the arc-melting furnace requires 450 kWh to melt one ton of steel, whereby the typical induction furnace requires 530 to 600 kWh per ton (5.77 to 6.54 10^6 Btu per ton tacit energy.) Tapping temperatures may have been lower, but the process likely involved chemical energy to assist the electric melting.

The energy use differences between the two facilities studied are probably not attributable to the melting furnace used to melt the scrap metal. It is evident from communications with industry experts that few differences exist between the two furnaces' total energy requirement. A casting yield survey conducted in 1997 by the Steel Founders Society of America (SFSA) included energy data on arc furnaces. A report based on this survey published in AFS Transactions, "Current State of Casting Yield,"(17) included a survey of melting energy consumption, which indicated that steel arc furnaces required 6.45 10^6 Btu of tacit energy to melt one ton of steel or 14.16 10^6 Btu per ton shipped.

Little information is available to indicate best practice facilities or processes for steel castings. The steel casting industry has been struggling to survive for many years and has not invested heavily in new technology. Methods of improving the efficiency of arc melting furnaces in the primary steel industry are not directly transferable to the smaller furnaces used by the steel casting producers. For example, oxygen enriched burner and foaming slag projects are not considered effective on the smaller furnaces typical of steel foundry operations. There is a need to review the melting methods used by the steel casting industry and provide economical methods of improving melting energy consumption.

RECOMMENDATIONS – STEEL MELTING

The literature review and interviews conducted for this study did yield the following general work practices that can assist steel foundries in improving existing furnace energy usage:

1) Automate and refine electrode level controls to provide maximum power capabilities throughout the melt cycle.
2) Minimize the time the lid is open for charging and the time the door is open for removing slag.

ALUMINUM CASTINGS – MELTING

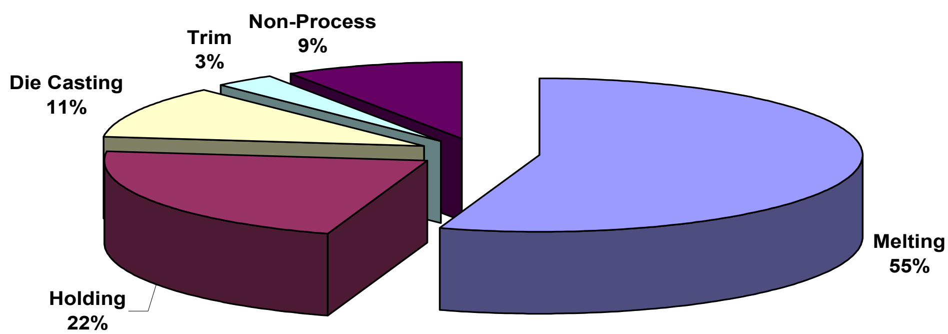
Aluminum casting facilities were forecast to ship 16 percent of total castings produced during 2003. Although aluminum facilities ship only 16 percent of the castings, this sector consumes 33.9 percent of the energy. Aluminum facilities consume between 60.56 10^6 Btu and 99.36 10^6 Btu tacit energy per ton of castings shipped, as discussed in the "Energy Use in Select Metalcasting Facilities"(2) and documented in Appendix A.

The energy used in a typical aluminum die casting facility is shown in Figure 19. Die casting facilities were forecast to ship approximately 70 percent of the aluminum casting shipments in 2003, as shown in Table 9 (pg. 10).

Molten aluminum used in aluminum casting facilities is supplied by either melting the aluminum in-house, or by bringing it in molten from a secondary aluminum facility.

Aluminum can be delivered to an aluminum casting facility in an insulated vessel and reheated to pouring 7temperatures. This can yield overall energy savings if the casting facility is in proximity to a secondary aluminum facility, because the metal is not cooled as an ingot or pig, but simply delivered to the casting facility in a molten state. There was no information available regarding the number of facilities receiving molten aluminum. One facility covered in the "Energy Use in Select Metalcasting Facilities"(2) used molten aluminum from a local smelter; however, the facility also had value-added processes present, biasing the results of the analysis.

Figure 19 - Delivered Energy Use In An Aluminum Diecast Facility



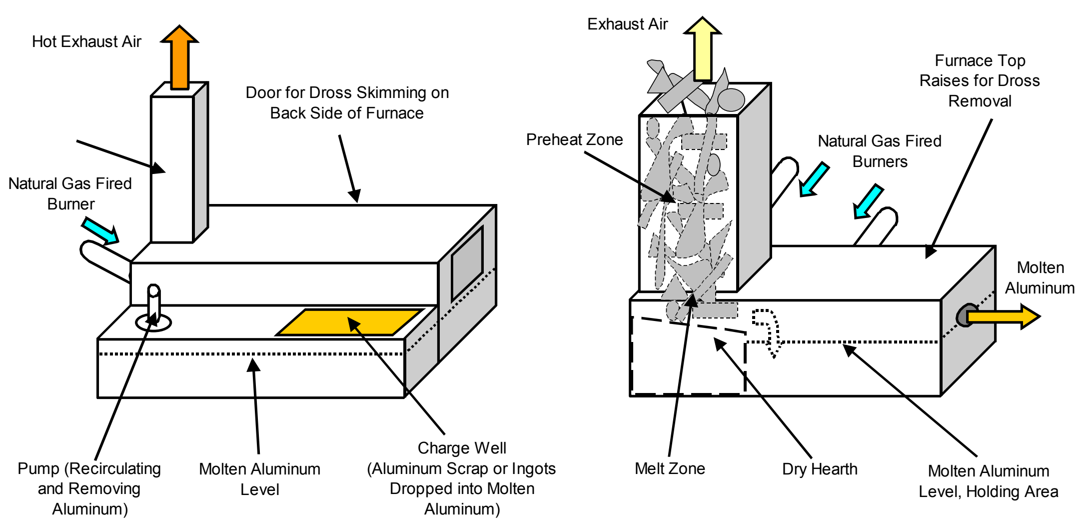
NADCA Energy Saving Manual, 1998 (12)

The types of furnaces typically used to melt aluminum in-house are the reverberatory furnace, stack melter, crucible, and induction furnaces. The reverberatory furnaces are widely used for melting and holding applications. They come in a variety of configurations and are often used as break down furnaces. The **reverberatory furnace** discussion in this report refers to a typical **wet** reverberatory furnace configuration that places the aluminum charge materials directly into a molten aluminum bath, as opposed to a **dry hearth** design that preheats/melts the charge on a dry hearth. Natural gas is the most common source of energy; however, fuel oil also can be used as an energy source. The furnace can be either rectangular or circular. In a rectangular furnace, the metal charge can be placed into the furnace through doors, but is typically placed into an open charge well connected to the main hearth. A fuel-fired burner is positioned on a sidewall to provide heat above the furnace hearth. The flames of combustion transfer heat to the metal by means of radiation and convection – directly and indirectly – by heating the walls and refractory furnace top. These furnaces typically operate at very low thermal efficiencies of about 20-25 percent, with most of the energy lost through hot flue gases.

A "stack melter" is a modified reverberatory furnace. The differences between these furnace designs is shown in Figure 20. In a stack-melter configuration, much attention is paid to improving the energy efficiency of the fuel-fired burner by better sealing the furnace and using a charging mechanism that allow the flue gases to preheat the aluminum charge materials. A skip charger or other device raises the charge metal up over the furnace into a steel and refractory- lined stack, alongside the furnace hearth. Below the stack is a dry hearth. This dry hearth supports the stack of solid charge materials. The exhaust gases exiting the furnace through this stack preheat and melt the scrap material, which then flows into the molten metal bath. This method of melting aluminum improves upon the reverberatory furnace in several ways. The molten metal bath remains at a high temperature, close to tapping temperature, since no cold solid materials are placed directly into the bath.

Since the solid material is not exposed to oxygen while being heated, nor placed into the molten bath, it is not oxidized, thereby minimizing slag formation. The stack-melter design exposes the charge material to hot gases that have a low-oxygen content, since the combustion process has already taken place over the molten bath. The reverberatory furnace has combustion taking place over the molten bath with cold charge material. The melt efficiency of the stack melter and the dry hearth design allow high melt rates from a relatively small furnace. This smaller holding capacity also reduces energy losses. One disadvantage is the height of the stack and charging mechanism, which may exceed 20 feet. The added equipment also requires additional maintenance attention.

Figure 20. Aluminum Reverberatory and Stack Melter Furnaces



Natural Gas Fired Reverberatory Furnace **Natural Gas Fired Stack Melt Furnace**

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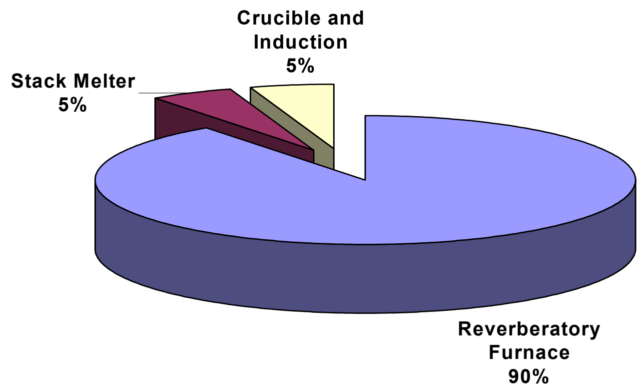
Induction furnaces are not widely used for melting large quantities of aluminum. They are considered to have high relative energy efficiencies when considering only delivered energy, and can melt multiple metal types, but have relatively high operating costs. These furnaces are similar to the ones previously discussed in the Chapter 1, Section 2, Induction Furnaces.

According to NADCA "Energy Saving Manual," 1998 (12):

> The crucible or pot-type furnaces consist of cast iron or clay bonded graphite crucibles (or pots) usually holding up to 1,000 pounds of aluminum. The crucible is surrounded by an annular space in which gas or oil burners generate the flame of combustion, although electric resistance heating can also be used. The heat is transferred to the metal charge through the walls of the crucible. Heat loss to the outside of the furnace is minimized by refractory walls of low thermal conductive materials.

The estimates shown on Figure 20 were obtained from communications with industry experts

Figure 21 - Estimated Aluminum Melting Furnaces Production*



*Foundry Supplier Interviews

and suppliers; there was no documentation available in the literature to assess the energy consumption of aluminum melted in different types of furnaces. Table 19 was assembled from information provided in the NADCA "Energy Savings Manual"(12) and describes the typical energy consumption required by different types of melting methods available to aluminum casting facilities. The wet reverberatory gas furnace dominates aluminum melting and, when properly maintained, uses an average of 1,350 Btu per pound of molten aluminum. Typical melt losses are also summarized in Table 19. These losses cannot be ignored in aluminum melting because they can vary from less than 1 percent to more than 5 percent using similar charge materials. The melt loss differences are primarily the result of furnace design differences rather than changes in charge materials.

Table 19 - Typical Energy Consumption for Aluminum Melting Furnaces

Furnace Type	Btu/pound			Melt Losses			Energy Efficiency			Tacit Energy Efficiency
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average	
Wet Reverberatory Gas	**1200**	**1500**	**1350**	**2%**	**5%**	**3.5%**	**32%**	**40%**	**36.0%**	**35%**
Wet Reverberatory Electric	638	819	728.5	1%	2%	1.5%	59%	76%	67.5%	21%
Dry Hearth Reverb Gas	1000	1200	1100	1.5%	2%	1.8%	40%	48%	44.0%	43%
Induction Coreless	638	819	728.5	1%	1.25%	1.1%	59%	76%	67.5%	21%
Crucible Gas	2500	7000	4750	3%	4%	3.5%	7%	19%	13.0%	13%
Crucible Electric	854	921	887.5	1%	2%	1.5%	52%	57%	54.5%	17%

Modified data from NADCA Energy Savings Manual 1998 (12)

The reverberatory furnace is the furnace used by the higher production aluminum casting facilities. Smaller facilities use crucibles and, in some cases, induction melting.

The analysis shown in Tables 20 through 22 assumes that the production of aluminum in the industry is all melted in reverberatory or stack melters. Literature searches and interviews with suppliers and aluminum casting facilities yielded the energy information presented in Table 20 for both styles of gas-fired furnaces. Interviews with industry experts indicated that the new stack melters melt no more than 5 to 15 percent of aluminum produced. The analysis of the differences in energy consumption between the two furnace types, therefore, assumed that stack melter production was 10 percent of the aluminum produced during 2003.

Table 20 - Aluminum Melting Furnace Energy Summary

	Melt		Tapped				Ship
	Gross Btu/pound	Melt Loss	Tapped Btu/pound	Tapped Btu(10^6)/Ton	Tacit Btu/pound	Tacit Btu(10^6)/Ton	Total Tacit Btu(10^6)/Ton
NADCA (12)	1,200-1,500	2-5%	1,399	2.80	1,434	2.87	4.41
Reverberatory Gas Furnace, Supplier Data	2500	5-7%	2,660	5.32	2,726	5.45	8.39
Reverberatory Gas Furnace AFS Article (25)	**1,975**	**5.5%**	**2,090**	**4.18**	**2,142**	**4.28**	**6.59**
Stack Melters, Supplier Data	1000	1.25%	1,013	2.03	1,038	2.08	3.19
Stack Melter AFS Article (25)	975	0.88%	984	1.97	1,008	2.02	3.10
Stack Melter, Die Cast Facility(26)	**703**	**1.25%**	**712**	**1.42**	**730**	**1.46**	**2.25**

For the reverberatory melting furnace, the NADCA energy estimates were about 1,350 Btu per pound, while information from suppliers and articles indicated that actual melting energy was as high as 2,500 Btu per pound melted. A reverberatory aluminum melt furnace, discussed in "A Melt Furnace Comparison: Stack Melter vs. Reverberatory Furnace," American Foundry Society(25), was chosen as a typical reverberatory furnace operating at an average of 1,975 Btu per pound melted. The stack melter energy consumption figures came from articles, as well as documentation from a stack melter die cast facility. The energy requirements varied between 703 Btu per pound to 1,000 Btu per pound of melt. The best practice die cast facility data was used for the stack melter estimate because the energy usage was available for a running furnace 18 months old and well maintained. This facility also had holding energy and equipment utilization records.

Table 21 gives the energy usage considered typical for a well-run and well-maintained stack melter and an average reverberatory furnace. Data in the "Actual" rows are the actual calculated energy requirement for the stack melter running at 50 percent utilization, 16 hours per day, and holding aluminum during the off shifts and weekends. The ratio of running energy (hourly melting energy) to actual energy of the stack melter was then applied to the running energy of the reverberatory furnace to estimate the actual energy requirements of the reverberatory furnace.

Table 21 - Aluminum Melt Furnace Comparisons							
	Melt		Tapped				Ship**
	Gross Btu/pound	Melt Loss	Btu/pound	$Btu(10^6)/Ton$	Tacit Btu/pound	Tacit $Btu(10^6)/Ton$	Tacit $Btu(10^6)/Ton$
Reverberatory Gas Furnace AFS Article (25)	1,975	5.5%	2,090	4.18	2,142	4.28	6.59
Reverberatory Gas Furnace Actual*	**2,418**	**5.5%**	**2,559**	**5.12**	**2,623**	**5.25**	**8.07**
Stack Melter, Die Cast Facility(26)	703	1.25%	712	1.42	730	1.46	2.25
Stack Melter Actual	**861**	**1.25%**	**872**	**1.74**	**893**	**1.79**	**2.75**

* "Actual" is the total energy usage including downshifts and weekends based on running at 50% of rated capacities. (Actual data on die casting operation stack melter.) Reverberatory "Actual" using the same ratio of energy differences as stack melter.

**Tons shipped considered 65% of melt. (Yield)

Table 21 also shows that the tacit energy requirements to melt aluminum in a reverberatory furnace are 8.07 (10^6) Btu per ton shipped while the best practice stack melter melts at 2.75 (10^6) Btu per ton shipped, both at 65 percent yield. This analysis also takes into consideration the melt loss differences between these two furnaces, since the differences are significant. The melt loss for the reverberatory furnace was estimated at 5.5 percent, and for the stack melter it was estimated at 1.25 percent. Actual melt loss numbers can vary and some of the stack melter sources reported less than 1.0 percent losses, while some reverberatory furnace users reported higher and lower losses. In reverberatory furnace melting, the high oxygen content over the bath and immersion of aluminum scrap into molten aluminum oxidizes the aluminum, forming dross that contains a high amount of aluminum metal. Certain fluxing methods can assist in releasing aluminum from the dross in the furnace. The losses are always higher than in a stack melter, however, where the aluminum is preheated by the low oxygen air stream and melted over the dry hearth.

Table 22 shows that an energy reduction of 10.84 10^{12} Btu of tacit energy would result from using well-maintained stack melters in all aluminum casting facilities.

Table 22 - Best Practice Aluminum Melting Energy Reductions			
Item	**Tacit Estimated 10^6 Btu/Ton**	**Estimated Ship Tons**	**Tacit 10^{12} Btu**
Reverberatory Gas Furnace Actual (90%)	8.07	2,036,700	16.44
Stack Melter Actual (10%)	2.75	226,300	0.62
Average	7.54		
Total-Estimated Energy			17.06
Stack Melter Actual (100%)	2.75	2,263,000	6.22
Difference per Year			**10.84**

RECOMMENDATIONS – ALUMINUM MELTING

Literature reviews and interviews conducted for this study yielded the following general work practices, which can assist steel aluminum casting facilities in improving existing furnace energy usage:

1) Use clean scrap – a pound of sand is worth 1.6 pounds of aluminum not melted. Sand also increases dross production.
2) Keep the furnace interior clean.
3) Ensure that refractory types used have the lowest thermal conductivities without compromising maintenance costs.

Recuperative burners have the potential to achieve energy savings of up to 30 percent, depending on the application. Recuperative burner systems on gas-fired melt furnaces have not been implemented for several reasons. First these savings would only be achievable with a constant high-temperature exhaust stream. It would also require high-temperature fans and more sophisticated gas-air mixers that could compensate for the changing temperatures of the exhaust steam. The application of preheated combustion air to gas burners, however, would primarily be applicable to existing reverberatory furnaces with high temperature exhausts of 800 to 1000°F, and not best practice stack melters that are capable of operating with exhaust temperatures of 250 to 400°F. The quality of the air in the exhaust air stream is also affected by fluxes and the type of scrap materials used, which would affect the design of air-to-air heat exchangers used for this application.

OTHER NONFERROUS ALLOYS – MELTING

Magnesium, copper, and zinc are other nonferrous alloys. These three alloys make up 5.4 percent of the estimated casting sector tons shipped for 2003 and consume 5.8 percent of the energy. The "Energy Use in Select Metalcasting Facilities" (2) documented the energy usage of four nonferrous facilities. The following assessment is based on facilities visited for the energy study. The casting facilities pouring these alloys are typically smaller shops, frequently with additional processing onsite, such as machining and assembly operations.

The summary of the energy usage per tons shipped is shown in Table 23 along with the theoretical energy requirements to melt one ton of the alloy. The overall energy used per ton shipped appears to be related to the theoretical energy required to melt a ton of the alloy. This would imply that the energy required to melt one ton of the alloy and the general melting methods are more significant factors than differences in casting processes and other operations present at the facilities.

Table 23 - Other Nonferrous Comparisons*

	Theoretical 10^6 Btu/Ton Melt	Tacit 10^6 Btu/Ship Ton
Magnesium Die Casting	1.07	67.8
Copper Based Greensand	0.604	37.3
Zinc Hot Chamber Die Casting	0.246	23.4

*Table 13 and Appendix A.

The magnesium die casting facility used electric melters at each die cast machine. Magnesium must be melted under an inert gas. It would be difficult to melt and transfer this alloy from a central melter. On the one hand, this method is not extremely efficient because the furnace must be sized for the largest metal usage at each machine regardless of what parts are being melted. On the other hand, the furnace has some inherent advantages because it is well sealed and insulated, as well as efficient in eliminating heat losses in other vessels or metal transfers. The "Energy Use in Select Metalcasting Facilities"(2) showed that the magnesium-melting furnace was operating at approximately a 52 percent utilization of the delivered energy. This is very good performance considering the tacit energy efficiency for this operation is only about 16 percent. The amount of tacit energy used, 67.8 mmBtu per ton shipped, was only slightly higher than required by the aluminum die casting facilities, at 60.6 mmBtu per ton shipped, as previously discussed.

The "Energy Use in Select Metalcasting Facilities" (2) study provided the only available energy use data on the magnesium melting process, based on a review of furnaces used to melt magnesium at die cast facilities. There is, however, another process used for melting and casting magnesium parts that has been installed in magnesium facilities that warrants further discussion.

The Thixomolding® process has been used successfully for certain magnesium parts. As reported on the Thixomat web site:(44)

> Thixomolding® is based on the principle that magnesium, aluminum and zinc alloys become semi-solid at temperatures between the liquidus and the solidus. Mechanical shearing of the semi-solid metal generates a thixotropic structure that allows these materials to be molded utilizing a process similar to plastic injection molding while eliminating the environmental impacts of die casting. Unlike die casting, the process does not require the handling of molten metals in separate melting and transfer systems…
>
> Simplified, the process is very similar to plastic injection molding, except the metal, currently magnesium, is being molded. The metal alloy is fed into the hopper and then through a connector into the mouth of the barrel. The solid material is then pushed through the barrel with a screw device. The material is simultaneously advanced while being electrically heated, converting it from a solid material into a thixotropic semi-solid state. After the material reaches the optimum stage of viscosity, it is injected at high speed into a closed die…

The advantages to this method of producing magnesium parts includes a near net-shape casting produced with a very high yield. The relatively simple method of heating raw magnesium materials to less than typical pouring temperatures may result in energy savings in both melting energy and yield. This process also may be applicable to zinc and aluminum castings. There is no energy use data available at this time comparing the thixotropic semi-solid state injection molding process to other melting and casting processes.

Both copper facilities studied used the greensand molding processes and small induction melters. Small induction furnaces were used because of the many different alloys required by the parts being produced. Induction melting can melt multiple alloy types, rapidly changing between alloys. The copper-based shops generated between 6 and 9 percent dross losses. This dross typically contained about 35 percent copper, which was sent out to smelters for processing. Fluxing or other methods used to recover the lost metal were not utilized for fear of causing metallurgical problems with castings.

The zinc facility visited used a natural gas-fired central melting furnace and hot-chamber die casting process. This facility uses a central-launder system to deliver metal to individual hot-chamber die casting machines. The lower amount of energy required to melt zinc is reflected in the lower total energy requirements to ship a ton of good castings. The zinc facility also created between 6 to 8 percent dross that contained 30 to 40 percent zinc.

RECOMMENDATIONS – Cu-Mg-Zn

The diversity of these nonferrous shops makes it difficult to draw any specific conclusions concerning best practice energy usage. The general conclusions drawn from this analysis are as follows:

1) A method of fluxing that does not affect casting metallurgy should be developed for copper and zinc alloys

2) The overall energy consumption level is primarily affected by the alloy melt energy.
3) Melting practice changes and yield improvements offer benefits in both reduced energy consumption and operating costs.
4) The thixotropic semi-solid state injection molding process needs to be evaluated to determine its energy savings potential for magnesium and other metals such as zinc and aluminum.

RECOMMENDATIONS – FERROUS AND NONFERROUS

The documents reviewed and interviews conducted to obtain information for this study also yielded some work practice recommendations, that will assist foundries in reducing energy consumption. The following are some general recommendations that apply to both ferrous and nonferrous melting:

1) Use clean scrap – one pound of sand charged means two pounds of iron or steel not melted and increases the slag generated.
2) Maintain minimum tapping temperatures that ensure quality castings.
3) Optimized scheduling – minimizes excessive holding power.
4) Proper Maintenance – reduced downtime on furnace saves energy.
5) Keep lids tight to reduce energy losses.
6) Refractory – maintain refractory thickness to factory recommendations.
7) Eliminate hot spots – many foundries perform infrared inspections to determine electrical problems and refractory problems prior to failures.
8) Streamline temperature measurement – automated furnace temperature and power controls will prevent overshooting temperature settings.

These work practice energy savings suggestions also were taken from the “Metal Melting Efficiency Project,” CCMA, Technikon, 2001(23) and “How Your Induction Melt Shop Can Survive the Energy Crisis,” Inductotherm, 2001(20).

SECTION 3 – MELTING ENERGY AND CO_2 EMISSION REDUCTIONS

Section 2 listed specific energy savings recommendations that were both process and work practice related. The literature searches, interviews, and visits conducted during the course of this study did not yield specific savings for individual work practice recommendations listed in Section 2. However, energy calculations for best melting facilities were available from operating facilities and suppliers. This section summarizes energy savings that result from using best practice melting methods and their resultant CO_2 emission reductions. First, however, this section discusses the melting efficiencies attained by the best practice melt furnaces and compares these results with other published energy studies.

The energy calculations performed in the melting best practice section of this chapter made assumptions concerning melting furnace operations because, in many cases, the specific facilities and documents reviewed had varying energy requirements for melting furnaces. To verify the validity of the best practice melting analysis, a comparison was made between the results in Section 2 with other published metalcasting energy studies. Table 24 is a comparison of the melting energy requirements for best practice and typical furnace operations with an energy study depicting typical melting energy requirements. The Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), in the Netherlands, published an energy manual, "Process Heating in the Metals Industry, Analysis Series No. 11,"(24) listing energy requirements of proven and emerging technologies or modifications to melting processes. CADDET's international members supplied the energy data to develop the table and also provided descriptions of successful energy reduction projects undertaken at member facilities.

Table 24 - Comparison of Melting Furnace Energy Studies

Type of Furnace	Melting Rate Tons/hour	Metal	Typical Specific Energy Consumption		Best Practice to
			kWh/Ton*	10^6 Btu/Ton*	Typical 10^6 Btu/Ton
Electric Arc	112	Steel	446.43 - 535.71	**1.52 - 1.83**	**1.54**
Cupola	5.6 - 22.4	Iron - Coke	220 - 375 lb coke/T	**2.86 - 4.88**	**2.81 - 4.03**
		Iron - Total			2.96 - 4.47
Coreless Induction	1.12 - 11.2	Steel	535.71 - 714.29	1.83 - 2.44	
		Iron	535.71 - 714.29	**1.83 - 2.44**	**1.84 - 3.31**
		Aluminum	491.07 - 714.29	1.68 - 2.44	
Reverberatory	5.6 - 112	Aluminum	1000 - 2222	**3.39 - 7.62**	**1.42 - 4.18**
Rotary	5.6 - 8.96	Aluminum	1250 - 1972	4.23 - 6.77	
	2.24 - 22.4	Iron	1250 - 2472	4.23 - 8.46	
Crucible	0.224 - 2.24	Aluminum	750 - 1250	2.54 - 4.23	

*Data taken from: "Learning from Experiences with Process Heating in the Metals Industry," (CADDET energy efficiency, Analyses Series No. 11, Centre for the Analysis and Dissemination of Demonstrated Energy Technologies, Netherlands, October 1993), page 117. Courtesy of L.White, CANMET(29)

The last column lists the energy ranges described in Chapter 1, Section 2 for best practice and typical melting facilities. As can be seen by comparing the last two columns, the delivered melt energy calculations closely match the CADDET manual.

The arc furnace energy is at the low end of the range; however, there is no information on the use of chemical energy for the CADDET study. The cupola ranges determined in this report are slightly lower than CADDET; however, for United States foundries, the average cupola melt rate is between 40 and 45 tons per hour, compared to the 5.6 to 22.4 tons per hour in the Netherlands study. The higher melt-rate cupolas, with larger working diameters, have inherently higher energy efficiencies, so these slight differences are expected. The best practice aluminum reverberatory furnaces have lower energy consumption in the United States. These furnaces were probably not considered in the 1993 CADDET study; however, the typical energy requirement of an aluminum reverberatory furnace is well within the ranges listed.

The energy efficiencies of best practice and typical melting furnaces discussed in Chapter 1, Section 2 are also listed in Table 25. This table calculates the delivered and tacit energy efficiencies. The steel arc furnaces are not listed because of insufficient information to accurately determine the chemical energy. The cupola-melting furnace data also includes coke efficiency, or the energy from coke, as compared to the iron energy requirement. Coke efficiency is often used to describe cupola operations.

Table 25 - Best Practice Melting Energy Efficiencies

Melt Method	Melt Energy 10^6 Btu/Ton	Tacit Melt Energy 10^6 Btu/Ton	Melt Energy Efficiency*	Coke Efficiency	Tacit Melt Energy Efficiency*
Iron Castings					
Heel Melting	3.31	10.39	36%		12%
Modern Batch Melting	1.84	5.77	65%		21%
Low-Efficiency Cupola	4.92	5.76	24%	36%	21%
High-Efficiency Cupola	3.25	3.84	37%	49%	31%
Aluminum Castings					
Gas Reverberatory Furnace	4.18	4.28	24%		23%
Gas Stack Melter	1.42	1.46	69%		68%

Note: Theoretical energy requirement; Iron = 1.200 Btu(10^6)/Ton, Aluminum = 0.986 Btu(10^6)/Ton.

***Efficiency calculations include all forms of energy used in the melting process and account for melt losses.**

The induction furnace energy efficiency is 36 to 65 percent delivered. However, the energy efficiency drops to 12 to 21 percent for tacit energy because of power generation and transmission losses. The cupola coke efficiency runs 36 percent for low efficiency operations and 49 percent for high efficiency cupolas. The total cupola energy efficiencies range between 24 and 37 percent and the tacit efficiencies range between 21 and 31 percent. The tacit energy differences for coke as a primary energy source do not deteriorate as much as in induction melting, which relies on electricity as a primary energy source. Aluminum melting reverberatory furnace efficiencies are 24 to 69 percent delivered, or 23 to 68 percent tacit efficiency. The natural gas used in aluminum melt furnaces has the best overall efficiency in a well run stack melter because it has very low tacit energy losses and an energy efficient design.

The best practice improvements described in Chapter 1, Section 2 are summarized in Table 26 to determine the kWh savings per ton of metal for all melting processes. The energy savings listed in Table 26 were used to generate the CO_2 and energy savings listed in Table 27. The CO_2 emissions factors discussed in the Introduction were applied to the different energy forms to determine the estimated CO_2 improvements corresponding to the energy improvements.

Table 26 - Melting Best Practice Energy Reductions							
	Delivered Energy per Ship Ton			Tacit Energy per Ship Ton			
Best Practice	Elect. kWh	Natural Gas 10^6 Btu	Coke 10^6 Btu	Electrical kWh	Natural Gas 10^6 Btu	Coke 10^6 Btu	Total kWh*
Induction Melting Best Practice							
Reductions per Ton Melt	430.00	0.00	0.00	1,324.40	0.00	0.00	1,324
Reductions per Ton Ship	716.67	0.00	0.00	2,207.33	0.00	0.00	2,207
Cupola Best Practice							
Reductions per Ton Melt	8.23	0.31	1.41	25.35	0.32	1.52	564
Reductions per Ton Ship	13.72	0.52	2.35	42.25	0.53	2.53	939
Aluminum Melting Best Practice							
Reductions per Ton Melt	0.00	3.38	0.00	0.00	3.46	0.00	1,014
Reductions per Ton Ship	0.00	5.20	0.00	0.00	5.32	0.00	1,559

*Tacit kWh is considered 10,500 Btu/kWh for electricity but 3,412 Btu/kWh for gas and coke since they are already in tacit energy.

A potential tacit energy savings of 42.17 10^{12} Btu per year would result from the utilization of best practice melting by iron and aluminum casting facilities at estimated 2003 production levels. This equates to a reduction of 2,936 10^3 tons of CO_2 emissions per year.

Table 27 - Estimated Best Practice CO_2 Reductions							
	CO_2 Pounds per Ship Ton				Estimated 2003		
	Electricity	Natural Gas	Coke	Total	Affected Ship Tons	Tacit Energy Reductions 10^{12} Btu/Year	CO_2 Reductions 10^3 Tons/Year
Induction Melting Best Practice	1,023.93	0.00	0.00	1,024	2,050,690	15.78	1,050
Cupola Best Practice	19.60	60.76	435.60	516	4,860,895	15.55	1,254
Aluminum Melting Best Practice	0.00	611.52	0.00	612	2,068,719	10.84	633
Total Best Practice Melting Reductions						**42.17**	**2,936**

The baseline energy consumed, as well as the CO_2 emissions per ton shipped for all alloys, are listed in Appendix A. The calculations show estimated CO_2 emissions by energy type, as well as by type of alloy.

The reductions listed in Table 27 show that the highest improvement potential is through modified cupola melting processes. The upgrades required are very capital intensive and yield the lowest per ton reduction of 516 pounds of CO_2; however, the high volume throughput of cast iron cupolas results in the high overall reduction potential. Induction melting process improvements result in the highest gain on a per ton basis, since the improvements are all in electricity, which has a very high tacit energy to delivered energy ratio of 3.08 (10,500 Btu/3,412 Btu). The aluminum improvement potential is very significant because the aluminum-casting sector is growing and the opportunity for new melt and production facilities will allow more energy efficient equipment to be incorporated into facility designs. Ferrous production levels are also forecast to increase; however, the ferrous metalcasting industry is returning to prior production levels and, in general, utilizing excess capacity rather than building new facilities. Magnesium castings represent a very small segment of the metalcasting industry at this time; however, are seeing increases in automotive and military applications. Magnesium, zinc, and copper alloys have the potential to reduce energy use and CO_2 emissions levels through melting efficiency improvements.

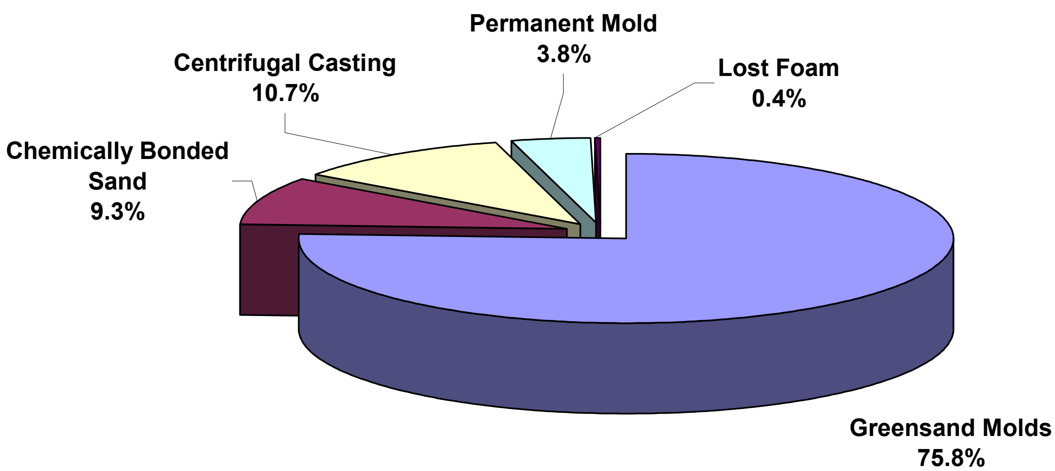
CHAPTER 2. METALCASTING

This chapter provides an overview of molding, or casting, methods used in the metalcasting sector by alloy type. The casting processes were analyzed to determine if there is a relationship between the casting process and energy usage. Casting yields and the affects of yields changes on energy and carbon dioxide emissions are also discussed by casting process.

SECTION 1. METALCASTING METHODS

Metalcasting molding or casting methods vary widely among various alloys and cast products. Certain types of castings are well suited to a particular casting process while others are not. Required production levels also dictate the molding process and type of pattern material best suited for the number of castings required. As can be seen in Figure 22 for iron casting processes, the predominant casting method is the greensand process. This process is well suited to very high production castings with reasonable quality levels.

Figure 22 - Iron Casting Processes



Sources: EPA Background Document 2002 (5)

CAST IRON MOLDING PROCESSES

The greensand process uses a sand mold prepared with a mixture of sand, clay, water, and typically seacoal as the organic component. The typical greensand molding processes consist of sand being squeezed, or somehow compacted, on a steel pattern. When the pattern is removed, the sand retains the form of the pattern. The mold consists of two halves, a cope (top) and drag (bottom). The cope is placed on the drag and iron is poured into the top of the cope, forming castings in the void formed by the pattern. Depending on the type of castings being produced, a core is sometimes used, such as when the castings produced require internal passages. A core is sand formed to the configuration of the casting's internal passages and typically held together by some form of organic binder. The predominant core binder type is a phenolic urethane-based binder system.

Chemically-bonded sand molds are prepared by mixing sand with binders, similar to those used to make cores. The mold holds the shape of the pattern by hardening on the pattern itself, due to the relatively fast reaction of the catalyst and the binder system. The molds are then separated from the pattern and the two halves are put together to form a mold. Chemically-bonded molding is much slower than the greensand process. Chemically-bonded molds may take several minutes or more to cure while a greensand-molding machine can make five molds per minute. The chemically-bonded molding process, however, uses less expensive pattern materials and forms a more precise reproduction of the pattern, and therefore a higher quality part.

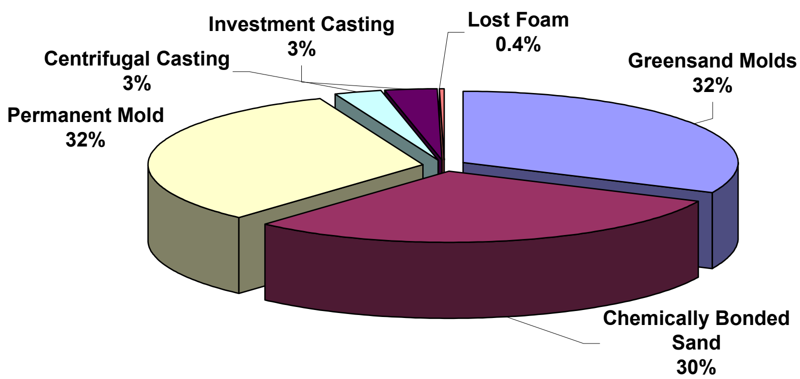
Centrifugal casting machines are used to make cast iron pipes and cylinder liners. They are not suited to other types of parts. The machines are relatively simple, use no sand, and tend to be very reliable. The configuration of the parts produced lends itself to a very efficient operation. Very small cores are sometimes used for certain types of pipe production. Other more specialized processes are used for specific casting requirements and include permanent molds and the lost foam process, which are also used for nonferrous alloys.

From an energy standpoint, the information analyzed for this study did not yield an advantage for a specific casting method. The facility energy profiles used in this report and listed in Appendix A are all greensand facilities, except for the cast iron pipe facilities. The tacit energy consumption of gray and ductile iron facilities was 29.7 10^6 Btu per ton shipped and 26.0 10^6 Btu per ton shipped, respectively. Literature searches did not yield any information on energy differences in molding processes and considered molding process energy usage at between 6 and 12 percent of total energy used in a metalcasting facility. Slight differences in molding process energy requirements are not likely to affect the overall energy profile of the facility. Other issues, such as machine utilization and casting yield, will likely overshadow any casting process energy differences. For example, cast iron pipe facilities have very low tacit energy consumption levels of 7.8 10^6 Btu per ton shipped. Cast iron pipe's very high yield, relatively simple and highly efficient centrifugal casting equipment, combined with no or very low core usage, yields a very energy efficient operation.

STEEL MOLDING PROCESSES

Steel castings use processes more adapted to the requirements of the steel products. Figure 23 shows the breakdown of steel casting processes. Steel casting production is evenly split among greensand, chemically-bonded, and permanent mold processes. The greensand process used by steel facilities differs from iron in that it cannot use seacoal or a similar additive containing carbon, which would cause problems with the lower carbon content of steel alloys. The permanent mold process used in steel is typically used to produce carbon steel railroad wheels in graphite molds. Three steel facility energy profiles are described in Appendix A, with two selected for this analysis. Both facilities used an electric melting process, one used arc and the other used induction. The tacit energy used per ton shipped was 40.70 10^6 Btu and 32.24 10^6 Btu, respectively. This is higher than the typical iron casting facility by about 33 percent. The steel metalcasters were much smaller than the iron facilities, which is typical of steel foundries. Steel production also requires heat treat operations, while finishing operations are very labor intensive compared to iron. One facility used chemically-bonded molds and the other used a combination of greensand and chemically-bonded processes. No conclusions can be drawn from the information reviewed for the molding processes. It appears that the smaller steel facilities with heat treat operations and higher labor requirements result in higher energy usage per ton of metal shipped.

Figure 23 - Steel Casting Processes
(By Tons Poured)



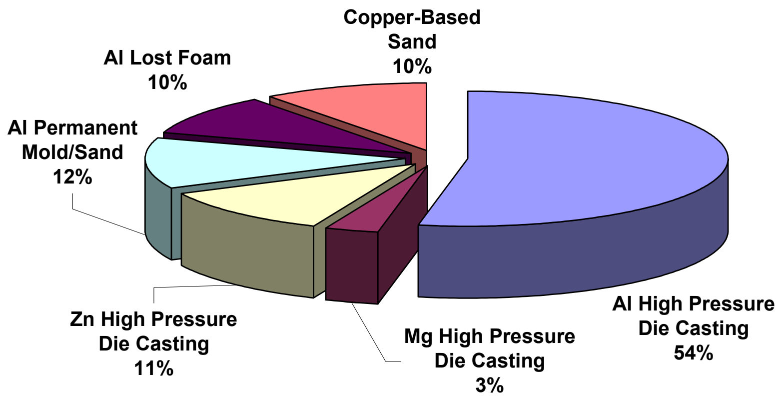
Sources: EPA Background Document 2002 (5)

NONFERROUS CASTING PROCESSES

Nonferrous casting processes are dominated by high-pressure die casting, at 68% of total, as shown in Figure 24. This process consists of water-cooled metal patterns as molds. The nonferrous alloy is then forced into the mold under pressure, forming a very high-quality part with high yields of 70 to 75 percent. This process is very common to nonferrous metals with lower temperature melting points, but is not applicable to ferrous alloys. Holding furnaces at die cast machines are sometimes used to superheat or maintain metal at ideal pouring temperatures. The magnesium casting process discussed in the "Energy Use in Select Metalcasting Facilities"(2) melted ingots in electric furnaces at the die cast machines, while the zinc die cast facility used central gas melters. The zinc facility then delivered molten zinc in gas-heated launders to hot-chamber die cast machines. Hot-chamber die cast machines at the zinc facility also used electric power to provide heat at individual die cast machine holding vessels.

The permanent mold process can take many forms, but generally uses a reusable mold of gray iron, high-alloy iron, steel, or graphite. The graphite molds are primarily used with iron and steel, and the ferrous alloy molds are used only for nonferrous alloys with lower melting temperatures. Different processes vary by the pattern material and the method by which the metal is introduced into the mold. Permanent mold processes do not use pressure to force metal into the mold, but can use a vacuum to assist in drawing metal into the mold.

Figure 24 - Nonferrous Casting Processes (By Tons Poured)



Data from Stratecast AFS Forecast and Trends 2002 (1)
EPA Background Document 2002 (5)

The lost foam casting (LFC) process, formerly called expendable pattern casting process (EPC), is a molding or casting process using gasifiable, expandable polystyrene (EPS) patterns. With this process, the pattern is made up of one or multiple EPS pieces bonded together to form the shape of the finished part. This pattern is placed inside a metal box with an open top, which is then filled with loose sand. The box is vibrated to cause the loose sand to pack tightly against the EPS pattern, filling open spaces within the pattern geometry. When metal is poured into the mold, the EPS pattern is consumed and the metal replaces the pattern. After cooling, the gating is removed from the metal box and the loose sand is then recycled.

The sand used in the lost foam process is coated with organics from the decomposition of the EPS patterns and requires processing to remove the organics from the loose sand. A side stream thermal sand reclamation process, reclaiming 5 to 7 percent of the molding sand used, is typically required to remove the organics from the molding sand to allow the sand to be reused in the molding process. From an energy standpoint, the use of the sand reclamation system increases energy consumption to levels higher than other molding processes.

The lost foam process is capable of exceptionally high surface finish and feature fidelity by very closely duplicating the pattern configuration. Also, this molding process is not constrained by the design limitation of other casting processes because loose sand is compacted inside the pattern to retain geometric contours. This method allows for the production of complex geometric configurations, dramatically reducing machining requirements and providing feature configurations not possible with other casting methods. The typical lost foam production line runs at 40 molds per hour.

The nonferrous process energy consumption levels are shown in Table 28. The average tacit energy used by different types of nonferrous casting facilities is shown along with the theoretical energy required to melt the alloys to tapping temperatures. No two facilities are exactly alike. However, the aluminum and magnesium die casting facilities are very similar in their energy consumption on a per ton basis and have similar theoretical energy requirements. The zinc hot-chamber die casting facility consumes only 36 percent of the aluminum energy usage for the entire facility, with actual melt energy requirements of only 25 percent as much as that required by aluminum. The reduction could be largely explained by the differences in theoretical melt energy because the melting energy used is typically 60 to 70 percent of total facility energy requirements. The copper-based sand energy requirements are 69 percent higher than the zinc facility with theoretical melt energy requirements 90 percent higher, again confirming that the casting or molding methods do not appear to have measurable differences in energy usage.

Table 28 - Theoretical Melt Energy vs. Facility Energy

	Tacit Energy 10^6 Btu/Ton Ship	Theoretical Melt Energy 10^6 Btu/Ton
Al High Pressure Die Casting	60.6	0.986
Mg Die Casting	67.8	1.070
Zinc Hot-Chamber Die Casting	23.4	0.246
Al Permanent Mold/Sand	99.4	0.986
Al Lost Foam	81.9	0.986
Copper-Base; Sand	37.3	0.469

The aluminum lost foam facility is a much higher energy consumer than the die casting facilities, which can be somewhat explained by the necessity of using thermal sand reclamation and additional environmental controls on process exhausts. Therefore, large lost foam shops appear to use more total energy per ton of castings shipped. The intricate shapes and low production rates also add to the high energy use on a per ton basis.

The aluminum permanent mold and sand casting facility had the highest energy usage. This facility is a "job-shop" with small reverberatory furnaces and gas crucible melting. The small production runs and varied equipment types add to the total energy per ton requirements compared to the larger production facilities.

Table 28 also depicts the actual "real world" energy use of metalcasting facilities compared to theoretical melt requirements. Many factors contribute to the differences between theoretical and actual energy requirements. The nonferrous alloys shown have theoretical requirements of 1 to 2 percent of actual energy use. This certainly indicates opportunities for improvements but not to the extent shown in the table. The efficiencies of all the issues discussed in this report are compounded when making this comparison. Overall melting tacit energy efficiencies are listed at between 13 and 43 percent, as shown on Table 19 (page 38). Operating efficiencies and equipment utilization reduce the tacit energy numbers significantly. Factoring in yield and scrap rates also reduce overall energy utilization. Additional casting processing, weather-related energy requirements, and air pollution control requirements all affect energy efficiency. Nonferrous processing energy requirements, other than melting, are also expected to be higher than with ferrous casting processes, since the castings are handled and processed one part at a time but weigh significantly less. The density of aluminum is about one third that of cast iron, requiring the processing of three times as many castings per ton of castings shipped.

In summary, there is no conclusive information available to show that the casting or molding method has any affect on overall energy consumption at a casting facility. The exception is the lost foam casting process, which has unique process capabilities. The differences noted throughout this report, as well as in Table 28, indicate that process- and plant-specific energy analyses would need to be performed to describe what energy reduction potential exists and to determine the best approach to reducing energy consumption.

SECTION 2. CASTING YIELD AND SCRAP

The relationship between customer shipments and tons melted in a metalcasting facility is referred to as "yield." The accepted foundry definition is the weight of metal that remains as a usable casting compared to the weight poured, including gating and risering systems. This definition may or may not include casting scrap. This discussion considers casting scrap separate from general yield considerations.

When molten iron is poured into a mold cavity to form a casting, more than just the weight of the casting is required. The system of "runners" and "risers" that feed the molten metal to the casting and continues to feed hot metal as the casting cools is called the "gating system." The metal is initially poured into the "pouring basin" where metal accumulates as it is fed into the gating system. The pouring basin is part of the gating system. The gating system consists of metal that does not become a part of the casting shipped to the customer. The gating system design is very complicated and affects the quality of the casting produced. Once the gating is removed from the casting, the gating metal is usually remelted in the melt furnaces and again poured into the mold.

The size and complexity of the gating system affects the energy required to make a good casting, as well as the labor required to process the casting into a good customer part (remove the gating). Complex and heavy gating systems, especially in steel foundries, are very labor intensive to remove from the casting and add to the energy requirements. Computer solidification models are used to assist foundries in designing minimum-weight gating systems while assuring quality castings.

Typical scrap and yield rates for many casting processes are shown in Table 29. Different molding processes and metals inherently have different yield numbers. The molding methods are chosen for many reasons, including the complexity of the casting and the overall production costs, which are heavily weighted by yield differences.

Table 29 - Estimated 2003 Casting Energy vs. Yield and Scrap

Alloy	Tacit 10^6 Btu/Ton Melt	Scrap Rate*	Tacit 10^6 Btu/Ton (Melt Less Scrap)	Casting Yield*	Tacit 10^6 Btu/Ton Ship	Yield and Scrap Losses
Gray Iron	18.33	5%	19.29	65%	29.7	38%
Ductile (Other than pipe)	16.05	5%	16.89	65%	26.0	38%
Ductile Iron Pipe	6.85	5%	7.21	92%	7.8	13%
Steel	19.26	4%	20.06	55%	36.5	47%
Al High Pressure Die Casting	40.70	4%	42.39	70%	60.6	33%
Al Permanent Mold/Sand	62.00	4%	64.58	65%	99.4	38%
Al Lost Foam	46.65	5%	49.11	60%	81.9	43%
Mg Die Casting	45.07	5%	47.44	70%	67.8	34%
Zinc Die Casting	16.81	4%	17.52	75%	23.4	28%
Copper-Base; Sand	17.72	5%	18.65	50%	37.3	53%
Titanium: Investment; Induction; HIP	34.32	4%	35.75	55%	65.0	47%
Other Non-Ferrous	10.46	7%	11.25	50%	22.5	54%

Note: Tacit Energy documented in this report except Titanium and Other Non-Ferrous
***Estimates from DOE/CMC Partners.**

Cast iron pipe foundries use centrifugal casting machines that typically produce over 90 percent yield. This process is limited in its application to other parts and can only be used for certain symmetrical castings such as pipes and cylinder liners. Also, cast iron pipe shops require the least energy to produce a ton of good castings, partially due to their high yield. Die casting and permanent mold processes with nonferrous alloys have high yields of 65 to 75 percent, whereas sand casting processes typically run 50 to 65 percent yield for most products.

Table 30 - Estimated 2003 Metalcasting Tons Melted*					
	2003 Estimated Tons Shipped	Shop Returns and % Scrap	Gross Casting Tons Produced	Casting % Yield	2003 Estimated Ton Melted
Gray & Ductile Iron; Sand	7,493,936	5	7,868,633	65	12,105,589
Ductile Iron Pipe	2,000,000	5	2,100,000	92	2,282,609
Steel, Railroad	628,830	4	653,983	65	1,006,128
Steel; Investment; Induction	114,736	4	119,325	55	216,955
Steel, All except Railroad & Investment	514,094	4	534,658	45	1,188,128
Al Investment; Induction	40,977	4	42,616	55	77,484
Al Die Casting	1,093,223	4	1,136,952	70	1,624,217
Al Permanent Mold	451,520	4	469,581	65	722,432
Al Lost Foam	304,014	5	319,215	60	532,025
Al Sand	373,266	5	391,929	60	653,216
Mg Die Casting	106,600	5	111,930	70	159,900
Zinc Die Casting	344,000	4	357,760	75	477,013
Copper-Base; Sand	311,600	5	327,180	50	654,360
Titanium: Investment; Induction; HIP	40,977	4	42,616	55	77,484
Other Nonferrous	86,227	7	92,263	50	184,526
Total Tons	13,904,000	4.6	14,568,641	62	21,962,065

*Information's taken from tables provide by DOE and CMC partners and AFS Metalcasting Forecast and Trends 2003. (1)

Because of scrap and yield losses, an estimated 21,969,065 tons of metal was melted to produce 13,904,000 tons of good castings in 2003, for an average yield of 63 percent (see Table 30). Melt losses are not considered in this discussion, but were evaluated in the melt furnace discussions in Chapter 1.

Table 31 - Estimated 2003 Energy & CO_2 Losses to Yield and Scrap				Losses	
Alloy	**Estimated Yield and Scrap Losses**	**2003 Benchmark Tacit Energy 10^{12} Btu**	**2003 10^3 Tons CO_2**	**Tacit Energy 10^{12} Btu**	**10^3 Tons CO_2**
Gray Iron	38%	162.6	11,187	62.2	4,279
Ductile (Other than pipe)	38%	52.4	3,494	20.0	1,336
Ductile Iron Pipe	13%	15.7	1,160	2.0	146
Steel	47%	45.9	2,993	21.7	1,413
Al High Pressure Die Casting	33%	96.0	6,217	31.5	2,039
Al Permanent Mold/Sand	38%	37.1	1,372	13.9	516
Al Lost Foam	43%	24.9	1,613	10.7	694
Mg Die Casting	34%	7.2	486	2.4	163
Zinc Die Casting	28%	8.0	515	2.2	144
Copper-Base; Sand	53%	11.6	780	6.1	410
Titanium: Investment; Induction; HIP	47%	2.7	187	1.3	88
Other Non-Ferrous	54%	1.9	353	1.0	189

Note: Tacit Energy documented in this report except Titanium and Other Non-Ferrous
*Estimates from DOE/CMC Partners.

Table 31shows the relationship between yield, energy usage, and CO_2 emissions. This analysis assumes that yield and scrap losses are proportional to energy losses. In reality, certain fixed energy requirements would not necessarily vary with yield, but these areas are not significant when compared to a foundry's overall energy profile. It is also probable that with improved yield performance, a foundry would be able to increase sales with existing facilities; therefore, the assumption that yield and scrap losses are proportional to energy losses is a reasonable approach to analyzing the effects of yield on energy consumption. This table shows that yield and scrap losses account for 13 to 54 percent of energy consumed or an average of 37 percent. For the gray iron casting sector, the actual energy needed to make one ton of good castings would be 18.33 10^6 Btu at 100 percent yield and no scrap. Yield and scrap losses, however, increase this energy requirement to 29.7 10^6 Btu per ton of good castings.

Taking this one step further, Table 31 also shows the energy losses and CO_2 emissions resulting from these yield losses. An estimated 175.1 10^{12} Btu of additional energy and 11,417 10^3 tons of CO_2 emissions result from yield and scrap losses.

Potential yield improvements and their effect on casting energy usage and CO_2 emissions are shown on Table 32. This analysis assumes that an improvement of 5 percent in casting yield is attainable in all areas except ductile iron pipe, where the improvement is 1 percent, due to this sector's high initial yield. This is or can be a combination of yield and scrap improvements, because they both have similar effects on energy and CO_2 emissions. Scrap has a much more pronounced effect on overall cost and labor requirements because it is usually processed in some way prior to being identified as scrap. An overall energy savings of 22.7 10^{12} Btu and emissions reductions of 1,471 10^3 tons of CO_2 per year could be achieved with an improvement of 5 percent in yield and scrap.

Table 32 - Energy & CO_2 Reductions with 5% Yield Improvement

Alloy	Estimated Yield and Scrap Improvements	2003 Benchmark Tacit Energy 10^{12} Btu	2003 10^3 Tons CO_2	Improvements Tacit Energy 10^{12} Btu	Improvements 10^3 Tons CO_2
Gray Iron	5%	162.6	11,187	8.1	559
Ductile (Other than pipe)	5%	52.4	3,494	2.6	175
Ductile Iron Pipe	1%	15.7	1,160	0.2	12
Steel	5%	45.9	2,993	2.3	150
Al High Pressure Die Casting	5%	96.0	6,217	4.8	311
Al Permanent Mold/Sand	5%	37.1	1,372	1.9	69
Al Lost Foam	5%	24.9	1,613	1.2	81
Mg Die Casting	5%	7.2	486	0.4	24
Zinc Die Casting	5%	8.0	515	0.4	26
Copper-Base; Sand	5%	11.6	780	0.6	39
Titanium: Investment; Induction; HIP	5%	2.7	187	0.1	9
Other Non-Ferrous	5%	1.9	353	0.1	18

Note: Ductile iron pipe improved 1% because yield losses start are at 8%.

Yield improvements are goals that metalcasting facilities strive for, but they are difficult to attain. Computer solidification modeling should be refined further to better describe all of the variables affecting casting quality, which would allow significant improvements to be made. Yield improvement in alloys such as steel would be particularly important because reduced yield losses would be accompanied by significant labor savings, improving the steel casting sector's competitive position. Other measures being investigated for potential yield improvements include research into the application of acoustic energy to reduce gating weight and improve casting quality.(45)

SECTION 3 – CASTING ENERGY AND CO_2 EMISSIONS REDUCTIONS

The metalcasting molding processes reviewed in Chapter 2, Section 1 did not indicate a measurable difference in energy used per ton of casting shipped, except for the lost foam processes higher energy usage. The lost foam process has unique capabilities that can reduce downstream costs or allow for better product designs. Downstream costs such as machining can be significantly reduced with the near, net shape parts produced. It also gives the casting designer more freedom to produce a part matching specific product needs, rather than meeting the needs of traditional molding processes.

Generally, the energy differences among the facilities reviewed were the result of the type of casting produced, production volumes, or the type of alloy melted. The specific type of alloy melted generally influenced the total facility energy requirements on a per ton basis. More specifically, the amount of theoretical energy required to melt a certain alloy affects the total energy consumption of the facility. This indicates that in order to make significant improvements in energy consumption levels, the melting methods and efficiencies are the primary issues that must be addressed. Melting efficiencies also can be affected by molding operating efficiencies, as well as other issues within a metalcasting facility that prevent high utilization of melting equipment.

The yield analysis in Chapter 2, Section 2 showed how process energy requirements could be reduced by improving yield. Many factors affect the specific types of molding process used, but in all cases designing a better gating system will improve relative yield numbers and reduce energy requirements. In some cases, yield improvements will improve production capacities and reduce labor requirements in the finishing areas. This is a significant issue at smaller facilities with lower volume production runs. The small shops tend to be very conservative in their gating designs to ensure that small runs produce acceptable quality castings.

As shown in Table 32, yield improvements of 5 percent in all alloys, except for ductile iron pipe at 1 percent, result in tacit energy reductions of 22.7 10^{12} Btu and CO_2 emissions reductions of 1,471 10^3 tons per year at estimated 2003 metalcasting production levels.

CHAPTER 3. OTHER ENERGY REDUCTION OPPORTUNITIES

Chapter 3 covers the energy reduction opportunities not discussed in Chapters 1 and 2. The subjects discussed are of a more general nature to document all major issues affecting energy usage. Section 1 analyzes the following areas of energy reduction opportunities:

- Plant Efficiency Discussion
- Heat Treating
- Ladle Heating
- Energy Conservation Programs

This chapter also summarizes the estimated energy reduction potential where sufficient information is available to perform the analysis. In Section 2, a review of the non-traditional methods of energy reduction is provided by investigating the potential for implementing combined heat and power applications to metalcasting waste heat sources.

SECTION 1 – ENERGY REDUCTION OPPORTUNITIES

ANALYSIS OF METALCASTING ENERGY REQUIREMENTS

The energy usage discussions in Chapters 1 and 2 analyzed specific parts of metalcasting plants and their comparisons to efficient production methods. These considerations were very process specific. Table 33 summarizes the actual plant profiles documented in Appendix A and compares the delivered energy per ton melted and shipped to the theoretical energy requirements to melt a ton of the alloy produced.

Table 33 - Facility Delivered Energy and Theoretical Melt Energy

Facility Type (From Appendix "A")	Facility Wide Delivered Energy		Theoretical Melt	Facility Wide Melt Efficiency*
	10^6 Btu/Shipped Ton	10^6 Btu /Ton Melt	10^6 Btu/Ton	
Gray Iron Cupola Melt	10.6	6.3	1.200	18.9%
Gray Iron Induction Melt	17.7	10.6	1.200	11.3%
Ductile Iron Pipe	6.3	5.8	1.200	20.8%
Ductile Iron, D Induction Melt	7.2	4.3	1.200	27.7%
Steel Arc Melting	19.0	18.8	1.225	6.5%
Aluminum HP Die Cast Gas Reverb.	31.7	22.2	0.986	4.4%
Aluminum Permanent Mold Gas Reverb.	71.9	46.7	0.986	2.1%
Aluminum Lost Foam Gas Reverb.	42.6	25.6	0.986	3.9%
Magnesium HP Die Cast Electric Melt	25.7	18.0	1.070	6.0%
Zinc Hot Chamber Die Cast Gas Melt	14.1	10.6	0.246	2.3%
Copper Based Induction Melt	37.3	18.7	0.469	2.5%

*Theoretical Melt Energy divided by Facility Wide Delivered Energy per Ton Melt.

The major energy consuming processes relate to tons melted rather than tons shipped, since the melt areas generally consume 72 percent of the total energy requirements, as previously shown in Figure 3. The theoretical energy required to melt and superheat the alloy being produced should therefore relate well to total energy consumption, unless some process differences such as melt or process efficiencies enter into the equation. The energy requirements per ton shipped are not discussed in this section, since they relate to yield and scrap rates previously discussed in Chapter 2, Section 3. The last column of Table 33 compares the delivered energy requirements to the theoretical melt requirements. This is not the same efficiency comparison made previously in this study on tacit energy; it was provided as an indication of overall plant equipment operating efficiencies. Since most of the energy consumption is melt related, the comparison of theoretical melt energy requirements to actual delivered energy is a general indicator of operating efficiencies (or utilization).

Since cast iron induction furnace melting requires less energy within a metalcasting facility, this melting method has the potential to have the lowest energy usage, but this is not always the case. The second column in Table 33 shows that the lowest per ton energy consuming facility is the ductile induction facility at 4.3 10^6 Btu per ton melted, which is assumed to use the latest heel melting furnace. The gray iron and ductile cupola shops have very similar energy requirements, even though the ductile pipe shops must heat treat their castings. This would indicate that the ductile iron pipe shops are melting more efficiently than the gray iron shops, which is to be expected because of their traditionally higher level of equipment utilization. This issue is difficult to quantify, however, because of a lack of sufficient data to describe plant operating efficiencies.

The gray iron induction melting facility used the older style heel melters, which are expected to consume delivered energy similar to high efficiency cupola melting (Table 18). The actual delivered energy consumed by the induction melting facility is 10.6 10^6 Btu per ton melted as compared to 6.3 10^6 Btu per ton melted for the gray iron cupola shop. This induction furnace shop was a much smaller facility than the cupola shop, as is typical of many induction furnace operations. The induction shop produced just over 13,000 tons of good castings per year, whereas the cupola shop produced in excess of 100,000 tons per year. This is an example of the energy differences typical of smaller facilities with older melting methods, and larger casting operations. The energy efficiency of a small facility would not be expected to approach that of larger one; however, the efficiencies achieved by both sized facilities could likely be improved. There is insufficient data to attempt to quantify the improvement potential. Furthermore, smaller facilities typically produce smaller production runs requiring different types of molding and core make equipment; they also use smaller, less efficient melting facilities. These differences make direct comparisons difficult.

The steel casting facility listed has an energy consumption of 18.8 10^6 Btu per ton melted, which is 77 percent higher than the gray iron induction facility just discussed. The steel melting methods are better than the older induction melting processes, but steel also requires heat treating operations and is very labor intensive because of the material produced. Also, steel facilities are typically small shops not able to take advantage of the efficiencies of larger casting plants.

The aluminum processes, listed in Table 33, bring up some interesting issues. The method of melting aluminum – using gas reverberatory furnaces – consumes large amounts of energy. The energy used by the average aluminum casting facility is 381 percent more per ton of metal melted than iron facilities, although theoretically melting aluminum requires 18 percent less energy. The discussion on melting methods in Chapter 1, Section 2 showed that the average aluminum casting facility required 25.73 10^6 Btu per ton melted, which could be reduced to 20.94 10^6 Btu per ton through the use of more efficient gas melting furnaces. However, this itself does not explain these significant differences. This change would still result in an energy consumption of 310 percent more than cast iron on a per ton basis, which averaged 6.75 10^6 Btu per ton melted. Again, this percentage is based on delivered, not tacit energy.

Another factor considered is that two to three times as many aluminum parts must be produced and processed to make up one ton of product as compared to ferrous alloys. This is offset somewhat by the less energy intensive molding and processing methods. Published reports on aluminum facility energy use list the melting and holding processes at 77 percent of total facility delivered energy.(12) This confirms the premise that aluminum facility energy use is highly dependent on the melting and holding process efficiencies.

The theoretical differences noted for aluminum casting energy requirements certainly warrant further investigation. Aluminum reverberatory furnaces are generally considered 36 percent efficient, however, can be as low as 20 to 25 percent in some instances.(12) The plant tours conducted as part of this study and other studies have shown that very inefficient melting and holding operations are typical of aluminum facilities. This, coupled with concerns for machine efficiencies, may be responsible for the relatively high energy usage. The relatively low cost of natural gas as an energy source may also be a factor.

This analysis indicates that melting efficiency improvements, beyond the melting facility improvements previously discussed, would certainly appear justified. It is not unusual to find an aluminum melting furnace servicing only one die cast machine, and dependent on the melting requirements and uptime of the die cast machine. This type of arrangement, rather than transferring aluminum from central melters, has sometimes resulted in furnaces operating at less than 20 percent of their rated capacity. Where central melting areas are used, there are also concerns with over-capacity and the use of many holding furnaces and heated vessels at die cast machines. Quantifying the potential for improvements would be very difficult, considering the limited site data reviewed. This issue is not peculiar to aluminum facilities; however it appears to be more significant with the nonferrous alloy facilities reviewed. The aluminum facilities represented in the "Energy Use in Select Metalcasting Facilities"(2) used as the basis for this report were also not the smaller facilities, as is the case with the other nonferrous alloys.

This high-energy consumption rate, as compared to theoretical requirements, implies that overall operating efficiencies, or equipment utilization, need improvement. It certainly would not be an unreasonable assumption to estimate that one third of the difference in energy consumption between aluminum and iron metalcasting facilities could be rectified by programs designed to improve machine and melting equipment utilization. Melting improvements would mean changes to holding capacities and melt furnaces to a more "just in time" method of aluminum melting and delivery. An improvement of one third of the difference would result in an average savings of 6.3 10^6 Btu per ton melted. This difference is shown in Table 34 and would result in savings of 21.61 10^{12} Btu per year in the aluminum alloy sector.

Other nonferrous alloys are also listed in Table 33 and vary considerably from theoretical energy requirements. Magnesium and copper-based alloys are similar to steel arc melting energy consumption, while zinc requires much less energy and is similar to iron induction melting. Magnesium has theoretical energy requirements most similar to iron at 1.070 10^6 Btu per ton melted. Magnesium's process specific requirements are many and the metal is typically melted at die cast machines under an inert gas. These nonferrous alloys are produced in smaller facilities and frequently have some form of specialized processing, making them difficult to analyze with the limited data available. Comparing energy consumption to the theoretical requirements indicates that general efficiency improvements also would be warranted, but would be very facility specific.

Table 34 - Potential Energy Savings, Operating Efficiency Improvements

Casting Process Type	Current Delivered 10^6 Btu	Delivered 10^6 Btu Change	Tacit 10^6 Btu Change	Tacit 10^6 Btu Change per Ton Ship	Estimated 2003 Ship Tons	Tacit Energy Savings 10^{12} Btu
Aluminum HP Die Cast Gas Reverb.	31.7	6.30	6.46	9.23	1,585,720	14.63
Aluminum Permanent Mold Gas Reverb.	71.9	6.30	6.46	9.93	373,266	3.71
Aluminum Lost Foam Gas Reverb.	42.6	6.30	6.46	10.76	304,014	3.27
Potential Savings						**21.61**

Heat Treating Operation

A heat-treating operation is typically a gas-fired oven that raises the temperature of a casting to a specific temperature for a specified length of time. Certain casting applications also require heat treating and liquid quenching of castings in high temperature oils. Heat treating of castings is performed on different alloys for different reasons. Some require structural changes in the alloy being produced that cannot be achieved in the casting process, while others are the result of using a casting process not suited to the metallurgy of the part produced. For example, certain ductile iron castings require heat treating operations due to insufficient cooling time available in the molding process whereas other alloys require heat treat and/or quenching operations regardless of the mold cooling time available.

In certain iron casting and aluminum processes, some types of castings may also need to undergo a low temperature heat treat to relieve internal stresses in the casting. In ductile iron, some parts must be heat treated due to insufficient cooling time in the molding process, causing too rapid a cooling of the part. The greensand molding process for ductile iron must have a long cooling time of 45 to 60 minutes to ensure proper structural properties. Cooling time is the amount of time between pouring molten metal to form a casting and removal of the cooled castings from the mold or casting process. Where insufficient cooling time is available, a separate heat treating operation is sometimes required. This is not the case with ductile iron pipe, however, because the centrifugal casting machines always cool the ductile iron pipe too rapidly, requiring some form of heat-treating operation. Most steel castings require heat treating at two different temperatures to ensure proper metallurgical properties.

Table 35 - Theoretical Energy Requirements by Metal Type*

	Steel		Ductile Iron
Heat Treat Temperature	1000°F	1750°F	1750°F
Theoretical Energy Req. (Btu(10^6)/Ton)	0.247	0.556	0.580

The only information available on the quantity of castings requiring heat treating operations is that steel and ductile iron pipe always require heat treating operations, while other alloys require some form of heat treating for certain types of applications. The energy required to heat treat iron and steel to appropriate temperatures was described in Chapter 1 Section 1. This information is summarized in Table 35.

Assuming that the castings are starting from room temperature, 0.580 10^6 Btu per ton of ductile iron would be required to raise the casting temperatures to 1,750°F. Thus, steel heat treating operations would require 0.247 and 0.556 10^6 Btu per ton, or 0.803 10^6 Btu per ton of good castings to heat treat every ton of casting shipments. The overall furnace efficiencies of annealing or heat-treating furnaces are considered to be about 30 percent, with the waste gas stream making up 50 to 60 percent of the losses.(24) The natural gas-fired furnaces are typically cold-air burner systems, meaning that the combustion systems use ambient air for combustion purposes.

One method that can be employed to reduce natural gas usage is to preheat the combustion air with the exhaust gas from the heat treat furnace. Exhaust temperatures are typically near the operating temperature of the furnace. To utilize exhaust gas, high temperature components must be used in the burner system and some form of automated or computer-controlled burner system must be installed to ensure proper furnace temperatures under varying load conditions. Burner combustion air preheat temperatures are also limited by the type of metal used to construct the air-to-air heat exchangers. Many factors influence the actual energy savings realized by preheating furnace combustion air; however, examples of energy improvements in running foundries in Europe indicate that a savings of 30 percent can be attained and even exceeded without switching to exotic materials or extremely expensive installations (CADDET Analysis Series 11, 1993 (24)).

Using the example described above and applying it to the estimated 2003 U. S. casting production would yield the savings shown in Table 36. Ductile iron pipe and steel castings are considered in this analysis. This is a conservative approach, since certain gray iron, ductile iron, and aluminum castings also require heat treat operations. Table 36 shows that 2.22 10^{12} Btu of energy in the form of natural gas could be saved from preheating combustion air.

Table 36 - Potential Energy Reductions, Heat Treat Improvements

	Theoretical Energy Requirements 10^6 Btu/Ton	Estimated Burner Efficiency	Energy Requirements 10^6 Btu/Ton	30% Estimated Reductions 10^6 Btu/Ton	Estimated 2003 Alloy Shipments	Tacit 2003 Energy Reductions 10^{12} Btu
Steel Castings	0.803	30%	2.677	0.803	1,257,660	1.04
Ductile Iron Pipe	0.580	30%	1.933	0.580	2,000,000	1.19
Total Potential Reductions						**2.22**

Another issue, which is not addressed in this report, is the amount of time castings are held at the higher temperature to achieve the necessary metallurgical benefits. The longer castings are held at heat treated temperatures, the more energy is consumed. There is a need to provide better guidelines, or research, into the appropriate heat treatment times for different castings to ensure proper metallurgical properties with minimum heat treatment times and energy usage.

Ladle Heating

Another area of energy use in the melting and pouring areas is the curing (drying) and preheating of ladles. These ladles are used in the transport of molten metal from the melting furnace to holding and pouring furnaces. Pouring ladles are also used to actually pour metal into molds, either manually or automated. Ladles used to handle molten metal are typically constructed of a steel shell with some form of refractory lining on the inside of the shell. This refractory material insulates the ladle to reduce energy losses and to protect the metal shell. When the refractory lining is replaced, it must be cured by heating the refractory for a period of time to drive moisture out of the refractory material. Prior to use, the ladles must be preheated to prevent the cold refractory from cracking and to drive out any moisture that may have collected in the refractory material since it was last used.

Ladles are typically heated by placing simple natural gas burners, or torches, into the ladles. These burners provide the energy to cure and preheat ladles in many different locations around the melting and pouring areas. These simple torches are estimated to be only 10 percent efficient due to their poor gas/air mixing efficiency and the use of open top ladles, which are inefficiently heated. More energy efficient designs have been available for many years; however, in an operating foundry the multiple locations needed for pouring and transfer ladle locations makes it difficult to install fixed ladle heaters. Premix burners and even electric heaters would be a major improvement, but require a fixed-ladle location and floor space to install and maintain the equipment. Some facilities have used a burner with regulated compressed air to guarantee an appropriate gas/air mixture. Using this method or other premix systems that avoid expensive compressed air would provide a much more energy efficient method of heating ladles. Better mixing can increase burner efficiencies from 10 to 30 percent, drastically reducing natural gas consumption. (Foundry Energy Conservation Workbook, AFS 1982 (9))

Research conducted for the "Energy Use in Select Metalcasting Facilities"(2) indicated that, in the steel arc melting facility visited, 1.02 10^6 Btu per ton shipped; or 4.9 percent of the total energy used by the facility, was used for ladle heating. Other sources listing ladle heating energy requirements include "Energy Conservation in Iron Foundries," Indian Foundry Journal, 2000(16) and "Energy Profile and Reduction of Specific Consumption of Energy in the Foundry," AFS International Cast Metals Journal 1980(15). Both listed ladle heating at 6 percent of total plant delivered energy usage.

Although the methods to reduce ladle heating energy requirements have existed for quite some time, the incentive to make improvements has not always justified the capital and labor costs. An increase in energy costs, especially natural gas prices, would make these methods more viable. Additional benefits can be gained by improving ladle refractory materials and ensuring that ladles are provided ladle covers.

No data is available on how many ladle heaters are used in metalcasting facilities are premix gas systems or electric heaters. It is assumed that this number is quite low and is estimated to be only 30 percent of total metalcasting facilities. Table 37 shows the energy savings that would result from improving ladle-heating efficiencies from 10 to 30 percent for all metalcasting facilities. These improvements are very significant and achievable for many facilities.

Energy Conservation Programs

The energy conservation documents reviewed as a part of this study all include some form of energy auditing and accounting programs. Identifying the energy consuming processes and their inefficiencies focuses attention on these areas and inevitably results in energy savings and efficiency improvements. The best practice facilities visited and foundry staff interviewed for this research study all provided details about energy usage and spoke intelligently about projects they were undertaking to improve energy performance. Likewise, they also discussed shortcomings and identified where they needed additional facility or work practice improvements. The exact improvements provided by an energy conservation program are very facility specific, but an organized energy conservation program is a necessary first step in making significant energy improvements.

Table 37 - Potential Energy Reductions, Other Opportunities

Potential Energy Improvement	Tacit Energy Savings 10^{12} Btu	CO_2 Savings 10^3 Tons
Operating Efficiency Improvements, Aluminum	21.61	1,240
Heat Treat Improvements	2.22	127
Ladle Heating Improvements	13.37	767
Total Potential Reductions	**37.20**	**2,134**

Energy and CO_2 Reduction Summary

The specific energy improvements listed in Chapter 3, Section 1 are summarized in Table 37. The total potential tacit energy savings of 37.20 10^{12} Btu results in carbon dioxide reductions of 2,134 10^3 tons per year at estimated 2003 production levels. These reductions are 8 percent of the forecast metalcasting energy consumption for 2003 and 7 percent of CO_2 emissions.

SECTION 2 – COMBINED HEAT AND POWER ANALYSIS

This section evaluates the potential for the application of combined heat and power (CHP) in the metalcasting industry. CHP is the generation of electricity with the use of waste heat produced during power generation to offset the need for purchased fuels such as natural gas or propane. CHP is desirable because it can be economically beneficial under the right conditions. It is also environmentally beneficial because the efficiency of a CHP system, with its use of waste heat, is much higher than the efficiency of a power plant. The greater efficiency results in reduced air emissions and more effective use of natural resources.

Power generation without waste heat recovery, called onsite **distributed generation**, also can be favorable when the cost of on-peak electricity is high relative to the cost of natural gas or other fuels used to operate the generator.

Metalcasting and foundry operations provide an opportunity to use purchased fuels for CHP, as well as the thermal (heat) and/or chemical energy stored in the process waste streams to generate electricity. Since the "waste" energy is essentially free, there is no additional fuel cost incurred for equipment operation, although maintenance costs merit consideration. Examples of electricity generation from waste energy are use of high quality (temperature) heat to generate steam for driving a steam turbine, or use of lower grade waste heat (400°F to 500°F) to drive an **Organic Rankine Cycle (ORC) turbogenerator**.

To address the opportunities described above, the potential for the application of CHP and use of waste energy is evaluated using the following scenarios:

1. "Packaged" systems such as a **microturbine** or similar small-scale generation with waste heat integrated into the process.

2. **Fuel cells** with waste heat integrated into the process.

3. Waste heat recovery to produce useful heat energy at a higher temperature using a **heat pump**.

4. Waste heat chillers or absorption heat pumps for heat recovery to provide cooling.

5. Trigeneration (i.e., combined cooling, heating and power).

6. Thermal (heat) and/or chemical energy stored in the process waste streams to generate electricity.

The prime movers most suitable for CHP are those that provide waste heat at a high enough temperature to be useable the greatest amount of time. Five different prime movers were considered for CHP use:

- **Reciprocating engine**
- Microturbine
- Stirling engine
- Organic Rankine Cycle turbogenerator
- Phosphoric acid fuel cell

Each of these prime movers was evaluated assuming (1) an output of 500 kW, and (2) that all waste heat generated was useable within a facility.

Onsite distributed generation (no heat recovery) was evaluated only for the microturbine and reciprocating engine, assuming an output of 500 kW. A generator output of 500 kW was chosen because it appears to be a small enough capacity to be suitable for use in most foundries.

Use of Waste Energy

Many foundry operations produce hot exhaust streams that offer the potential for electricity generation through process heat recovery. While there may be many possibilities, four process operations were selected as the most viable candidates for an initial screening:

- High efficiency cupola melting furnaces (cast iron)
- Aluminum stack melters
- Steel casting heat-treat processes
- Ductile iron pipe heat-treat processes

The data used in all analyses represents, to the greatest extent possible, average values that are representative of those that would be encountered in the field. Thus, the results are general in nature and are intended to serve only as a guide to potential application.

Focus of Effort

Candidates for electricity generation have been evaluated based on energy cost reduction only. There may be numerous reasons, other than energy cost benefit, for a facility to consider on-site power generation. These include the desire to lower air emissions to help protect the environment, and to improve the reliability of electric utility service, production rate, and security. Thus, depending on circumstances surrounding a given facility, there may be additional considerations. The other potential benefits, such as increases in production rate, are not quantified but are noted as appropriate.

Evaluation Methodology

When financial benefits are the overriding factor for consideration of power generation, the two most likely scenarios are generation without heat recovery (i.e., onsite **distributed generation or DG**) in order to reduce peak period costs, or the use of CHP. As discussed previously, with CHP, the waste heat from the generator (prime mover) is used to meet a heat duty otherwise served through purchased utilities such as natural gas. However, another potential alternative is power generation with simultaneous heating and cooling, also called **trigeneration**. To produce cooling from a heat source, a thermally-activated **absorption or adsorption chiller** can be used. The foundry industry does not appear, however, to have a significant need for refrigerated mechanical or thermal cooling, so this option may not be economically feasible on the basis of energy alone.

While refrigerated chilling may not be feasible on the basis of energy cost, there may be other economic benefits such as use of a low temperature source to improve production rates can be achieved by shortening the product-cooling period. Other benefits may be gained from having a more constant temperature source available. While these may offer significant financial and environmental benefits, the focus of this study is on energy cost benefist only, so trigeneration and the related methods for thermal cooling (absorption chillers, waste heat chillers, etc.) will not be considered further. However, since there may be instances where refrigerated cooling is used, information has been included for those who wish to consider this further.

When DG is the selected option, the prime movers used will always require use of a purchase fuel like natural gas, fuel oil, or propane. This allows the generator to be started on demand during the on-peak period when electrical costs are highest. A waste energy source is not normally used to drive DG, although it is possible if the time availability of a waste energy source can be predicted.

Whether considering onsite distributed generation or CHP, the systems must be sized to meet base load requirements. While this is important for onsite DG, it is particularly important for CHP. The reason for this is that CHP systems must meet both electric and thermal load requirements for as long a period as possible to optimize economic performance. Poor planning and design with regard to thermal load matching can severely hamper the economic benefits of CHP, lengthening the time frame for return on investment and potentially reducing the likelihood that future energy cost reduction projects will be considered by management.

Quantitative Evaluation Approach

The quantitative evaluations for CHP and onsite DG were initially to be carried out in part using a screening tool developed by the Department of Energy (DOE). Review of the screening tool, however, revealed that its use in the current context would be impractical given the nature of foundry operations; thus, the screening tool was not used. Instead, different approaches were selected for evaluation of CHP, DG, and energy recovery systems for power generation. These approaches are discussed below.

As noted earlier, proper thermal load matching is important to the success of any CHP system. For the purpose of this study, however, all waste heat generated by the prime mover is assumed to be useable during all times the generator is operating. To aid the reader in determining applicability, typical uses of the waste heat and temperatures are provided, based on the prime mover used. Additionally, except when the “potential” to generate power is being evaluated (discussed later), generator output is limited to 500 kW from natural gas-fired prime movers (engines). This relatively low generator output helps to keep the analysis as practical as possible with respect to matching the generator output to facility need.

Having stated that the generator output is a 500 kW natural gas-fired unit and that all waste heat is used continuously, the economic performance of CHP and onsite DG can be fairly easily estimated. To allow prediction of financial benefit, the following assumptions were applied to the analysis:

- Natural gas is $6.63/10^6$ Btu .

- Coke is $180/ton ($6.42/10^6$ Btu).

- Electricity is $0.04475/kWh average.

- Electricity is $0.080/kWh during on-peak time.

- Operating hours based on a 16-hour day and 5-day work week, 50 weeks per year. (Since the processes under consideration may have widely varying operating hours at any given facility, benefits are shown based on 40 percent and 90 percent availability during operating hours.)

While it is always best to evaluate the financial performance of electricity generation on a net present value (NPV) basis, for simplicity, ROI is used with equipment and installation cost, based on rule of thumb estimates. Actual installation costs can vary widely and may makeup a significant portion of the cost of any generation project. This implies that rule of thumb estimates, although experienced based, should be used for screening purposes only.

Evaluating the Potential for Power Generation

As discussed previously, foundry processes present not only the opportunity to use purchased fuels for electricity generation, but also the opportunity for electricity generation using the thermal and/or chemical energy stored in the process waste streams. An example of the use of thermal energy is the heating of a cooler stream with a hot stream. This can be done directly by mixing the hot and cold streams (more efficient) or indirectly (less efficient) with a heat exchanger.

An example of the use of the chemical energy stored in a waste stream is the combustion of relatively cool (~500°F to 800 °F) cupola exhaust to create a very hot exhaust, which is then used to pre-heat blast air. Combustion is possible due to the chemical energy contained in the constituents of the cool cupola exhaust. Thus, blast air preheating improves overall cupola efficiency because the heat supplied by the preheated blast air does not have to be supplied by purchased fuels such as natural gas or coke. The operation of preheating blast air may be of particular interest to an energy manager who is trying to find ways to reduce facility costs. The manager may ask “How efficient are we at using the waste energy from our processes? Is burning cupola exhaust to preheat blast air the best use of the energy in the exhaust?” It would be difficult, if not impossible, to extract all of the necessary information to make such a determination from an equipment specification sheet. Thus, evaluation of waste energy sources for their potential to perform work (e.g., generate electricity, drive a pump or fan) requires a different approach. The approach selected is based on the first and second laws of thermodynamics, and is called “**exergy**” or “availability” analysis. The term exergy is used in this report, but the two are equivalent.

Exergy analysis was selected because it provides a measure of the theoretical potential to generate electricity from the waste energy sources available. The following sections provide a brief overview and demonstration of the use of exergy analysis and the insights that can be obtained with its application. A detailed explanation is beyond the scope of this report, but more information can be found in the references (Kotas[33], Cengal[31]).

A Perspective on Exergy

Generally, most facility personnel and vendors use the term "energy" in a generic way with regard to quantity and use (e.g., Btu/hr, kW). What is often not fully taken into account is the “quality” of the energy source in question. As a result, it may go unnoticed that all Btus are not equal in value, and the potential to perform work and minimize the impact of process operation on the environment may be unrealized. For example, electricity that costs \$0.04475/kWh has an equivalent cost of approximately \$13.11/10^6 Btu. This is approximately twice as much as natural gas at \$6.63/10^6 Btu, on a Btu basis. This is because electricity represents “pure” exergy; it is completely available to perform work. Natural gas on the other hand, must be converted, with all related inefficiency, before it can be used to perform work. Consider a fan requiring a 200-hp prime mover. The fan can be driven with either an electric motor or a combustion turbine. A 200-hp electric motor is approximately 95 percent efficient whereas the combustion turbine may be only 30 to 35 percent efficient, both on a second law basis. Thus, electricity has a greater value, due to its greater capacity to perform work.

To determine the work (electric generation) potential or exergy change of a process, the "dead state," or state "0," must be defined. The dead state is generally the atmosphere at a temperature of 77°F, but it can be different depending on the situation. The change in exergy of a stream in any process moving from one state (1) to the dead state (0) can be determined from the following relationship:

$$\Delta\phi_{1\rightarrow 0} = -\{(\Delta h)_{1\rightarrow 0} - T_e \times (\Delta s)_{1\rightarrow 0}\}$$

The term $\Delta\phi_{1\rightarrow 0}$ represents the change in exergy, $\Delta h_{1\rightarrow 0}$ the change in **enthalpy**, and $\Delta s_{1\rightarrow 0}$ the change in **entropy**, in moving from state 1 to state 0. The temperature T_e is taken to be the "dead state" temperature of 77°F (536 R).

Once the exergies are known, the second law efficiency (η_{II}) for any process can be estimated by the following formula:

$$\eta_{II} = (\Delta\phi \text{ (desired output stream)} \div \Delta\phi \text{ (energy source)}) \times 100$$

When fuels such as natural gas are involved, the term $\Delta\phi$ (energy source) is substituted with the standard chemical exergy of the fuel. The standard chemical exergy represents the potential of the fuel to do useful work, such as generate electricity. Values of standard chemical exergy are provided in the text by Kotas.(33) When the standard chemical exergy is not available, the lower heating value (LHV) of the fuel can be used with only small error (~5%). The following example demonstrates this application.

Current high efficiency, tank-style water heaters have an efficiency of about 58 to 62 percent. This efficiency is based on the first law of thermodynamics, which says that energy cannot be created or destroyed but only converted from one form (natural gas) to another (hot water and heat losses). Thus, a high efficiency water heater converts 58 to 62 percent of the heating value of the natural gas to hot water Btus. If exergy analysis is applied to determine the second law efficiency, however, you get a very different picture.

These assumptions apply to the water heater:

- The natural gas is 100 percent methane.
- The "dead state" for water is 60°F at 14.7-psia.
- The chemical exergy (ξ_{ch}) of the natural gas is approximately equal its LHV and the contribution of air is neglected.
- The LHV of methane is approximately 21,584 Btu/lb.
- The water is heated from 60°F to 120°F.
- The first law efficiency of the water heater is 60 percent.
- The water flow rate is 3 gpm.

Since hot water is the desired output stream, using steam table values for saturated water at 14.7-psia (1 atmosphere) and referring to the equations above, the changes per pound of water are:

enthalpy change on heating: $\Delta h\ (\text{water})_{60°F\rightarrow 120°F} = (87.97 - 28.06)$ Btu/lb = 59.91 Btu/lb
entropy change on heating: $\Delta s\ (\text{water})_{60°F\rightarrow 120°F} = (0.1646 - 0.0555) = 0.1091$ Btu/lb*R

exergy change when water is brought in equilibrium with the dead state:

$\Delta\phi$ (water)$_{120°F \rightarrow 60°F}$ = 59.91 – (519) x (0.1091) = 3.2871 Btu/lb

The natural gas requirement for water heating (Qf) is:

Qf = Δh (water) = (3 gal/min x 60 min/hr x 8.34 lb/gal x 59.91 Btu/lb) ÷ 60% = **89,937 Btu/hr**

Qf ÷ HHV = 89,937 Btu/hr ÷ 21,584 Btu/lb = 4.1668 lb natural gas /hr

The rate of change in exergy of the water as it flows into equilibrium with the dead state is:

$\Delta\phi$ (water)$_{120°F \rightarrow 60°F}$ = (3.2871 Btu/lb x 3 gal/min x 60 min/hr x 8.34 lb/gal) = **4,935 Btu/hr**

The second law efficiency is:

η_{II} = (4,935 Btu/hr ÷ 89,937 Btu/hr) x 100 = **5.5%**

The second law efficiency indicates the water heater is only about 5.5 percent efficient, compared to the first law efficiency of 60 percent. This means that of the work potential contained in the chemical energy of the natural gas, only about 5.5 percent remains in the hot water. An exergy balance around the hot water heater reveals that the exhaust contains exergy. However, the sum of the exergy of all output streams does *not* equal the exergy of the input streams (natural gas). To the contrary, using the first law, the sum of the enthalpy of all output streams around the water heater *will* equal the heating value of the natural gas.

One may then ask "where did the work potential go?" It did not "go" anywhere. It was simply destroyed through the process of combustion and heat exchange and cannot be recovered. Thus, making hot water from a high quality source like natural gas is a poor use of resources and is truly a very inefficient process.

PRIME MOVERS FOR COMBINED HEAT AND POWER AND ONSITE DISTRIBUTION GENERATION

This section provides a brief overview of the different prime-mover technologies available to drive onsite distributed generation and CHP systems using purchased fuels. The following overview considers the prime movers currently available. Actual operating conditions may pose special limits to the application of a given prime mover.

Reciprocating Engine

A **Reciprocating engine** uses an organic fuel, such as fuel oil, propane, biogas (digester or landfill), or natural gas, which allows the possibility for fuel switching capability. Incorporating capability for fuel switching is a strategic move that permits a facility to operate on the least expensive fuel. Other concerns, however, such as environmental emissions, may also drive fuel choice.

Gaseous fuels may be preferable in most continuous use operations due to ease of transport and lower emissions. Fuel oils typically find greatest application for back-up generation. Low-grade heat (~180°F to 240°F) is typically recovered from engine cooling water and exhaust for use in CHP applications. Due to the lower temperature, the waste heat from reciprocating engines may be most useful in metalcasting operations for preheating combustion air, make-up air, or other low temperature applications.

Reciprocating engines tend to be noisy and are usually more expensive to maintain than other prime movers. However, reciprocating engines have higher power generation efficiencies than many other prime movers, particularly in the smaller sizes. The primary characteristics of reciprocating engines are:

- Efficiencies from 28 to 32 percent or higher for larger engines;
- Approximately 40 percent of input fuel energy is recoverable as low-pressure steam or hot water;
- Somewhat noisy operation;
- Very short start-up time;
- Installed cost of approximately $1,200/kW to $1,600/kW, with heat recovery;
- Maintenance costs of $0.009/kWh to $0.015/kW; and
- Single unit capacity of 50 kW to 5,000 kW, with banking of units for larger output needs.

Microturbines

A Microturbine is a centrifugal generator and operates in a fashion similar to a combustion turbine, except that the turbine rotor spins at a much higher speed. Like reciprocating engines, microturbines typically use an organic fuel, such as fuel oil, propane, or natural gas, but a single unit can be configured to operate on more than one fuel to allow for fuel switching capability. Recently, there has been more activity related to use of biofuels.

One of the biggest drawbacks of a microturbine is their low-generation efficiency. This inefficiency is further impacted by the high temperature of the combustion air; cooler combustion air equates to higher efficiency. While technology advances have allowed efficiency increases, efficiencies are still low relative to reciprocating engines.

Although reciprocating engines may have a greater efficiency, microturbines are quieter and less expensive to maintain. The primary characteristics of microturbines are:

- Efficiencies from 22 to 26 percent;
- Approximately 60 percent of input fuel energy is recoverable as low-pressure steam or hot water;
- Relatively quiet operation;
- Installed cost of approximately $1,000/kW to $2,000/kW, with heat recovery;
- Maintenance costs of $0.002/kWh to $0.01/kWh
- Rapid start-up time, but slower than reciprocating engines; and
- Single unit capacity up to 250 kW, with banking of units to meet greater capacity needs.

Stirling Engine

Stirling engine technology has been in existence for a long time, although recent advances have improved the technology to the point where it is available for commercial use. Thus far, most applications of Stirling engines have required a purchased fuel such as natural gas. Clean, high temperature (>1,400°F) waste heat sources can also be used, however, making hot cupola exhaust a candidate if the exhaust can be sufficiently cleaned.

The basic principle of operation is such that there are few moving parts, and those parts that do move do not come in contact with combustion gases. These factors combine to keep maintenance costs low. Stirling engines are reported by manufacturers to be quiet and cost effective to maintain, much like microturbines.

Initially, the power generation efficiency of Stirling engines was on the order of 10 to 15 percent. At least one manufacturer now claims generating efficiencies up to 30 percent (natural gas-fired) under the proper operating conditions. The primary characteristics of Stirling engines are:

- Efficiencies from 12 to 30 percent;
- Approximately 50 percent of input fuel energy is recoverable as hot water;
- Ability to fire on natural gas or use high temperature (>1,400°F) waste heat;
- Maintenance costs similar to microturbines;
- Quiet operation;
- Installed cost of approximately $1,000/kW to 2,000/kW, with heat recovery; and
- Units with a capacity of 55 kW are now in the market. Banking of units is possible to meet larger capacity needs.

Fuel Cell

A **Fuel cell** operates much like a battery, except that they are able to utilize hydrogen as a fuel on a continuous basis. Because fuel can be supplied continuously, fuel cells, in theory, can operate indefinitely. In practice, the electrode catalysts become poisoned and performance diminishes over time. Like batteries, the output from fuel cells is direct current (DC) and an inverter is necessary to convert DC to the alternating current (AC) required to operate most facility equipment.

Table 38. Summary of Fuel Cell Technologies[1]

Fuel Cell Type[1]	Commercially Available (yes/no)	Anticipated Availability	Output (kW)	Generation Efficiency (%)	Waste Heat Application	Installed Cost ($/kW)
Phosphoric Acid	yes	Available	100 - 200	36 - 42	LP steam, hot water, cooling	> $5,000
Solid Oxide	no	Next 3 years	1 - 10,000	45 - 60	HP & LP steam, hot water, cooling	----
Molten Carbonate	no	Next 3 years	250 - 10,000	45 - 55	HP & LP Steam, hot water, cooling	----
Alkaline[2]	no	-----	0.3 - 5	~70	hot water	----
PEM[3]	no	Next 5 years	3 - 250	30 - 40	hot water	----

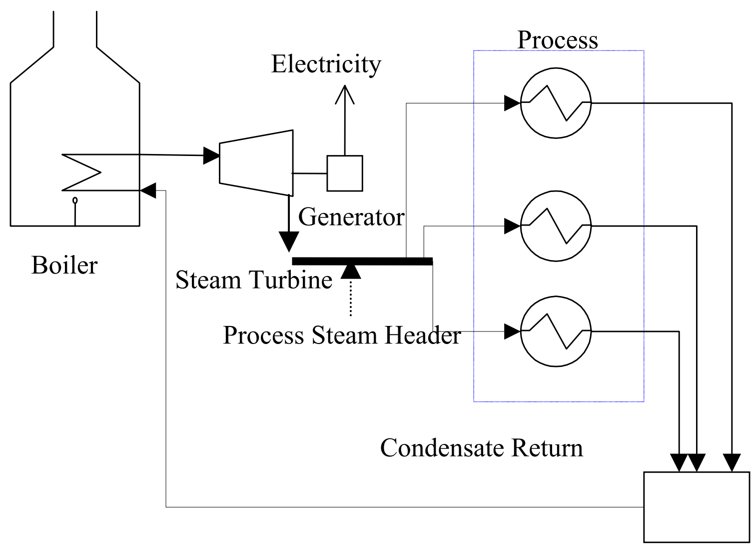
1. Composed from review of numerous sources, a few of which are included in the appendix.
2. Fuel cells have essentially zero emissions when hydrogen is used as the fuel source. When hydrogen is extracted from a feedstock such as methane, emissions result.
3. PEM - Polymer Electrolyte Membrane – Used primarily in the space program.

There are several types of fuel cells, each classified by its mode of operation. At present, the phosphoric acid fuel cell (PAFC) is the only commercially available fuel cell. Other fuel cell types are under development and should start to become available in the next one to three years. Table 38 provides an overview of fuel cell technology.

Steam Turbogenerators

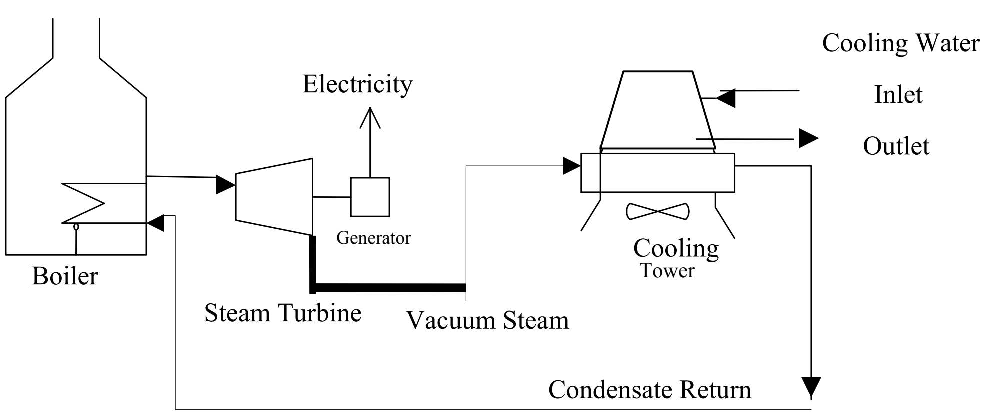
Steam turbines accept steam from an external source, such as a heat recovery boiler or natural gas-fired boiler. Heat recovery boilers use waste thermal energy to generate steam. Regardless of how the steam is generated, a turbine expands steam from a higher pressure and temperature to a lower pressure and temperature. During expansion of the steam, the turbine imparts power to a shaft that is used to turn a generator for production of electricity. Steam turbines are usually classified as back-pressure (Figure 25), condensing (Figure 26), or extraction-condensing turbines (Figure 27), although actual systems can be combinations of the three. Back-pressure and extraction turbines are usually found in paper mills and in the process industry where there is a need for steam at intermediate or low pressures. Condensing turbines are most often used in power plants and are also the most likely candidates for use on foundry processes where hot exhaust can be used to generate steam in a waste heat boiler. The most appropriate configuration depends on the facility needs.

Figure 25: Typical Back-Pressure Steam Turbogenerator*



*EnVise LLC, Madison, WI

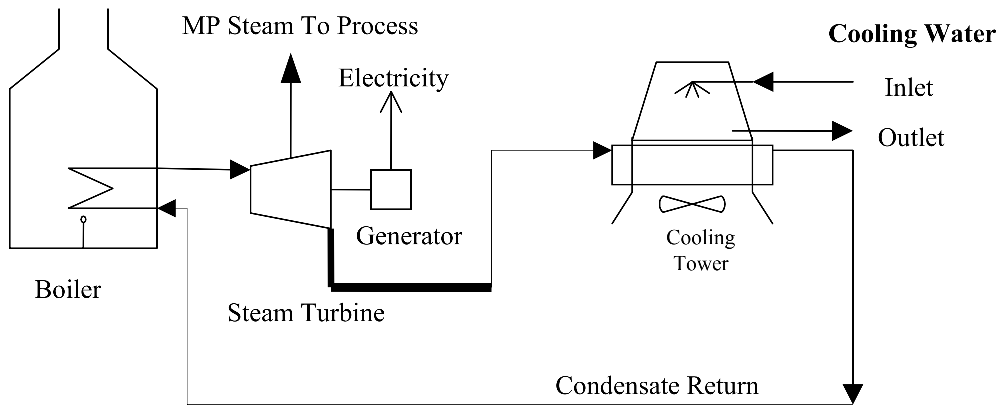
Figure 26: Typical Condensing Steam Turbogenerator*



*EnVise LLC, Madison, WI

Steam turbogenerators represent a mature technology that can be very cost effective in combined heat and power applications. Condensing steam turbines are typically not cost effective unless the fuel source is free – as with waste heat – or very low cost. Examples where condensing turbines may be cost effective are in the use of waste heat boilers for steam generation using hot cupola exhaust.

Figure 27: Extraction-Condensing Steam Turbogenerator*



*EnVise LLC, Madison, WI

Determining the generation system (boiler, turbine, or generator) efficiency with a steam turbine is somewhat more complicated than for other prime movers. The second law efficiency of the boiler is used, not the first law efficiency, as is reported in much of the literature. (The first law efficiency is also the efficiency estimated from a boiler combustion analysis.) For example, an optimized power plant boiler might have a first law efficiency (η_I) of 86 percent, but a second law efficiency (η_{II}) of only 43 percent. Steam turbines typically have second law (isentropic) efficiencies in the range of 38 to 80 percent, depending on a number of factors like size, speed, and type (back-pressure, condensing, etc.). The electricity generator coupled to a steam turbine typically has a second law efficiency of 95 to 96 percent. This implies that 95 to 96 percent of the shaft energy used to turn the generator is converted to electricity. The second law generation efficiency can be determined simply by dividing the electricity output in Btu/hr by the fuel energy input in Btu/hr. With this in mind, the following is a summary of the primary characteristics of steam turbogenerators:

- Combined steam turbine/generator second law efficiencies range from about 35 to 77 percent, depending on size, speed, and mode of operation. Smaller systems tend to have lower efficiencies. Second law system efficiencies, which include the turbine/generator and the boilers (η_{II} =43% for gas-fired), range from about 15 to 34 percent. Cogeneration or trigeneration system efficiencies can be much higher.

- When heat is recovered from a backpressure turbine, it is usually recovered as low – to medium – pressure steam or hot water.

- Relatively low maintenance costs of about $0.004/kWh.

- Relatively quiet operation.

- Installed costs, excluding the boiler, typically range from $400/kW to $1,000/kW depending on system size.

- Has single unit capacities of 50 kW to very large power plant turbines with capacities greater than 100 MW (100,000 kW).

Organic Cycle Turbogenerator

The Organic Rankine Cycle (ORC) turbogenerator operates in a cycle similar to the condensing steam turbine shown in Figure 26. One of the fundamental differences is the use of a specialized fluorocarbon refrigerant instead of water as the working fluid. The properties of the refrigerant provide an advantage of the ORC over a steam cycle turbine. The ORC turbogenerator can operate at a relatively low temperature (225°F to 500°F), making it suitable for recovery of low-temperature waste heat for power production.

A disadvantage of the ORC turbogenarator is that its second law efficiency is somewhat lower than for the typical steam turbogenerator. Additionally, the field application of ORC turbogenerator technology is relatively new in comparison to steam turbine technology. However, the capabilities of the ORC allow its use in cases where a low temperature heat source is readily available and steam turbines or other technologies are not applicable. The following is a summary of the primary characteristics of ORC turbogenerators:

- System second law efficiencies, which include the turbine/generator and the heat source, range from about 5 to 14 percent, depending on the application. When applicable, cogeneration or trigeneration system efficiencies can be much higher.

- Approximately 50 percent of input fuel energy is recoverable as waste heat in the form of low-pressure steam or hot water.

- Information on maintenance cost were not readily available, but would be expected to be similar to or less than a steam turbine cycle, given reports of reduced turbine blade erosion. This is due to the use of the fluorocarbon refrigerant as a working fluid instead of water.

- Relatively quiet operation.

- Installed equipment costs (without heat recovery) range from about $1,500/kW to $3,000/kW depending on system size.

- The net electrical output for single units from one manufacturer (Turboden) ranges from 450 kW to 1,500 kW.

WASTE HEAT RECOVERY OPPORTUNITIES

By definition, combined heat and power means the generation of power and use of the waste heat produced by the generator to offset heat from purchased fuel. There are a variety of ways to recover and use waste heat. The following discussion provides some background on the potential applications.

Recuperative Heat Exchanger

A recuperative heat exchanger, or recuperator, is a more specific name for an exchanger designed for gas-to-gas heat transfer. Recuperators are very common in industry. An example is blast air preheating using hot cupola exhaust. Heat exchangers come in a variety of types and materials, depending on the intended use.

The lower the design approach temperature, the more efficient the heat exchanger will be at performing its intended function. However, lower approach temperatures require a greater exchanger area, which increases cost. The optimized exchanger or exchanger network will be the one balanced for performance and cost. Fouling, low flow rate, and corrosion can reduce the performance of heat exchangers, so it important that they be properly sized and maintained just as other equipment.

Typically, recuperators used to preheat blast air are inefficient relative to heat transfer area. This is because the "dirty" cupola exhaust requires a larger spacing between tubes to prevent plugging. The larger spacing implies lower heat exchanger area for a given size exchanger.

The efficiency of a heat exchanger is typically denoted by its "effectiveness." Effectiveness is based on the first law and is the ratio of the heat recovered to the heat available. The effectiveness of a typical recuperator is 60 to 70 percent. The effectiveness of a blast air preheater is generally much lower. The higher the effectiveness of a recuperator, the greater the recovery of heat and the more cost-effective the operation.

When considering energy cost reduction alternatives, it would be prudent to consider improving the performance of existing systems through increases in heat transfer area. For example, a facility that is presently realizing a hot blast air temperature of 1,000°F with the existing preheater may be able to add exchanger area to increase the temperature to 1,200°F or greater. This can offer numerous advantages in addition to energy cost reduction, including but not limited to:

- Equipment redundancy, which requires no additional maintenance skills.

- Potential ease and relatively low cost of installation.

- Potential reduction in the oxidation of product, which can result from lower blast air temperature.

Thermal Chiller

Absorption and adsorption chillers are types of thermally activated chillers. While absorption and adsorption chillers differ in the sorbent used, they both provide a net cooling effect given heat input. As previously noted, there appears to be minimal need for refrigerated cooling in foundry and metalcasting operations and such options are not specifically covered in this report. Some potential applications are office air conditioning, sand cooling, and dehumidification of cupola hot blast air. For informational purposes, a brief summary of absorption and adsorption chillers is provided.

<u>Absorption Chillers</u>
Several types of absorption chillers are currently available, including:

- Indirect-fired, single-effect absorption;
- Indirect-fired, double-effect absorption; and
- Direct-fired, double-effect absorption.

An indirectly-fired absorption chiller operates on hot water or steam. A direct-fired unit typically requires combustion of natural gas.

Single-effect absorption chillers use a single stage for regeneration of lithium bromide salt with water as a refrigerant, although ammonia is also used. Double-effect units use an additional generator, condenser, and heat exchanger for greater heat recovery. Using the **coefficient of performance (COP)**, double-effect chillers can be up to 40 percent more efficient than single-effect chillers; however, the cost is also 30 to 50 percent higher. A summary of some of the characteristics of absorption chillers is provided in Table 39.

Adsorption Chillers

Adsorption chillers have been used primarily in Europe and Japan, but appear to be gaining acceptance in the United States. Adsorption chillers operate in a manner similar to that of absorption chillers, except that the sorbent is silica gel rather than lithium bromide. The silica gel is reported by one manufacturer to be non-corrosive and to require changing far less frequently than absorption chillers. The use of sorbent appears to make a significant difference in life-cycle costs, with the adsorption chiller being the most cost effective. A summary of the characteristics of adsorption chillers is provided in Table 39. This information is a compilation of data from numerous sources, a few of which are included in the appendix (Ryan$_{(38)}$, Trane$_{(39)}$).

Table 39. Summary of Absorption and Adsorption Chiller Characteristics

Criteria	Single-effect Absorption	Double-effect Absorption	Adsorption
Coefficient of Performance (Btu/hr-output/Btu/hr-input)	0.5 to 0.7	~1	0.4 to 0.6
Salt Used	Lithium Bromide[1]	Lithium Bromide[1]	Silica Gel
Capacity (ton)	380 to 1,650	380 to 1,650	20 to 170[2]
Installed Cost ($/ton)	$400 to $600	$600 to $800	$500 to $800
Maintenance Cost ($/ton)[3]	$20 to $35	$20 to $35	Comparatively Minimal

1. Lithium bromide is corrosive to equipment.
2. Capacity can be increased with parallel units.
3. Maintenance costs depend on capacity; larger capacity units are less costly to maintain.

Heat Pump

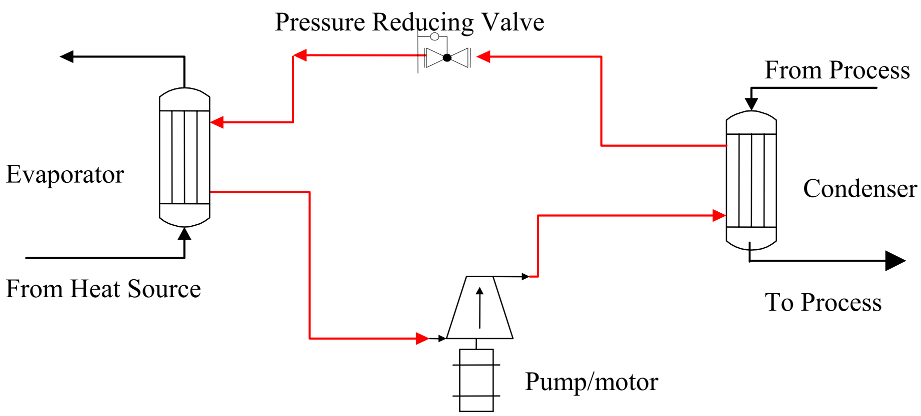
Heat moves freely from higher temperatures to lower temperatures, which is the basis for the operation of heat exchangers such as recuperators. To move heat from a lower temperature to a higher temperature, a heat pump is required. A typical closed-cycle heat pump uses an electric motor and compressor to compress refrigerant vapor. The compressed refrigerant vapor condenses in the “condenser” (see Figure 28), transferring heat from the refrigerant to raise the temperature of the process fluid. The condensed liquid refrigerant leaves the condenser at a lower temperature, but at relatively high pressure. The low temperature, high-pressure refrigerant then passes through a pressure reduction valve to reduce pressure. The refrigerant, now at lower temperature and pressure, moves through the evaporator where heat is *removed* from the heat source by refrigerant evaporation. The low-pressure refrigerant vapor then leaves the evaporator and moves to the compressor, where the cycle repeats. A typical schematic for a closed-cycle electric heat pump is provided in Figure 28.

Generally, the performance of a heat pump is limited by its COP, its upper operating temperature limit of 200°F to 250°F, and temperature lift. Temperature lift is the difference between the refrigerant condensing and evaporating temperatures. The condensing and evaporating temperatures are a function of the heat exchangers used, the heat source, and the heat sink (stream to be heated) temperatures. The higher the temperature lift, the lower the heat pump efficiency.

If the temperature lift required is large enough, multi-staging of heat pumps can be used to minimize the temperature lift across each unit. Other factors that impact the economic performance of heat pumps include:

- The cost of electricity and the cost of the heat replaced by the heat pump.
- The size of the heat load to be transferred by the heat pump.
- Annual heat pump operating hours.
- How well the heat pump capacity has been matched to its intended purpose.

Figure 28: Closed Cycle Heat Pump with Mechanical Vapor Recompression (MVR)*



*EnVise LLC, Madison, WI

Economics drive the final configuration. The COP for electric closed-cycle heat pumps discussed here typically ranges from approximately 2 to 4, depending on the application. However, there are several other different types of heat pumps used in industrial settings. Overall, the COP for heat pumps ranges from approximately 3.0 to 30 depending on cycle configuration, working fluid, and temperature lift. Table 40 shows the cost of heat delivered by a heat pump as a function of the cost of electricity. Table 41, included for comparison, is the cost of heat supplied by natural gas at 70 percent efficiency.

As can be seen in the Table 40, the cost of heat delivered with a heat pump decreases proportionally with COP. Additionally, comparison of Table 40 and 41 indicates that heat pumps are most favorable in facilities with low electric costs but higher heating costs.

Table 40. Cost of Heat Delivered by an Electric Heat Pump*

Electricity Cost ($/kWh)	Cost of Delivered Heat ($/$10^6$Btu) Heat Pump Coefficient of Performance (COP) 3	5	8	10	20	30
$0.02	$1.95	$1.17	$0.73	$0.59	$0.29	$0.20
$0.03	$2.93	$1.76	$1.10	$0.88	$0.44	$0.30
$0.04	$3.91	$2.35	$1.47	$1.17	$0.59	$0.40
$0.05	$4.89	$2.93	$1.83	$1.47	$0.73	$0.50
$0.06	$5.86	$3.52	$2.20	$1.76	$0.88	$0.60

*Gluckman, R, Industrial Heat Pump Manual; Technical and Applications Resource Guide for Electric Utilities, EPRI, Palo Alto, Ca, 1988.(42)

Table 41. Cost of Heat Delivered by Natural Gas at 70% Efficiency

Natural Gas Cost ($/$10^6$Btu)	Cost of Delivered Heat ($/$10^6$Btu)
$2.00	$2.86
$3.00	$4.29
$4.00	$5.71
$5.00	$7.14
$6.00	$8.57

Consider a facility that is paying an average natural gas cost of $6.00/$10^6$ Btu and an average electricity cost of $0.04/kWh. At an average electricity cost of $0.04/kWh and a COP of 5 (Table 40), the delivered cost of heat is $2.35/$10^6$ Btu. An increase in the COP to 10 reduces the cost of heat delivered to $1.17/$10^6$ Btu, a reduction of approximately 50 percent. Additionally, a heat pump with a COP of 5 provides heat at a cost of $2.35/$10^6$ Btu, which is 365 percent less than $6.00/$10^6$ Btu natural gas that has a delivered cost of $8.57/$10^6$ Btu. The difference can have a significant impact on economic return.

Because of the number of configurations of heat pumps available, it is difficult to assign a "rule-of-thumb" cost for installation. However, "costs for closed-cycle mechanical heat-pump systems range from $50,000 to over $200,000/$10^6$ Btu of heat delivered; no predictable relationship exists between size of unit and cost.... simple paybacks for industrial heat-pump applications, where the primary goal is energy-cost reductions, are typically 2 to 5 years."(41)

While the high operating temperatures in a foundry may limit application, heat pumps can be considered in those cases where lower temperatures are involved. There are several potential heat pump applications in a foundry:

- Dehumidification of blast air (prior to pre-heating) and use of the reject heat for preheating of combustion air for the cupola or other furnace.
- Dehumidification and cooling of sand cooler air, with use of reject heat for other adjacent applications that require heating.
- Controlling humidity in metal scrap storage areas to prevent oxidation.
- Space heating for office or plant areas.

APPLICATION OF PRIME MOVERS TO POWER GENERATION

Each of the prime movers discussed earlier is evaluated for use in a CHP application. The generator output is fixed at 500 kW and all waste heat is assumed to be adequate to offset some process operation.

Table 42. CHP Options Operating at 40% of Facility Hours (1,600 hr/yr)

Parameter	Prime Mover Operating at 40% of Facility Hours				
	Reciprocating Engine	**Micro-turbine**	**Stirling Engine**	**ORC**	**PA Fuel Cell**
Generator(s) Capacity (kW)	500	500	500	500	500
Electric Rate/Fuel Rate (10^6 Btu basis)	1.97	1.97	1.97	1.97	1.97
System Efficiency for Power Generation (%)*	30%	23%	28%	12%	38%
Fuel Use (10^6 Btu /hr)	5.69	7.42	6.10	14.23	4.49
Useable Waste Heat (10^6 Btu /hr)	2.2	4.8	3.1	8.5	2.1
Waste Heat Temperature (F)	180 (cooling water) 800 (exhaust)	500	145	100	160
Typical Waste Heat Use	LP steam, Hot water	LP steam, Hot water	hot water	hot water	hot water
Purchased Electricity Offset (kWh)	800,000	800,000	800,000	800,000	800,000
Electricity Cost Reduction ($/yr)	$35,800	$35,800	$35,800	$35,800	$35,800
Purchased Fuel Offset (10^6 Btu /hr)	2.2	4.8	3.1	8.5	2.1
Fuel Cost Reduction ($/yr)	$23,373	$50,995	$32,934	$90,686	$22,310
Generator Fuel Cost ($/yr)	$60,458	$78,858	$64,776	$151,144	$47,730
Installed Cost ($/kW)	$1,350	$1,500	$2,200	$2,000	$5,000
Annual Maintenance ($/yr)	$8,800	$7,200	$7,200	$8,000	$6,000
Simple Return (yr)	Never	1,017	Never	Never	578

*Efficiency = power output/fuel input (BTU/hr basis)

As can be seen in Table 42 and Table 43, the quantity and temperature of the waste heat source is variable, depending on the prime mover. As a practical matter, many foundries may not have use for enough low temperature heat to economically justify a CHP instillation. In these cases onsite distributed generation to reduce on-peak electricity costs may be a better option, depending on peak period utility charges. Existing backup generators may be candidates for peak shaving, *if* they are designed for extended duty operation. If back-up generation is being considered, the incremental cost to convert to continuous duty natural gas-fired generators may not be difficult to justify.

Tables 42 and 43 address different CHP options at 40 percent and 90 percent of facility hours. Whether for CHP or onsite generation, the ratio of the electric rate to natural gas rate (Btu basis) and maintenance costs will play a significant role in determining economics. Note that none of the options evaluated show a reasonable return on investment. Table 43, which is based on 3,600 operating hours, shows a better return on investment, but still far too long to be practical. Those options where simple return on investment (ROI or simple return) that are marked "never" because they are considered operating expenses. The limiting factor in these cases is the relatively low electric to fuel rate ratio. Typically, the rate ratio needs to be at about three or better for CHP instillations to have any potential for financial success. Also note that while the ORC does not show a ROI, this is the case when using natural gas as a fuel. The capacity of the ORC to use waste heat in the range of 225°F to 500°F may make it more suitable for power generation through waste heat recovery, which means that ORC may still find applicability.

Table 43. CHP Options Operating at 90% of Facility Hours (3,600 hr/yr)

Parameter	Prime Mover Operating at 90% of Facility Hours				
	Reciprocating Engine	Micro-turbine	Stirling Engine	ORC	PA Fuel Cell
Generator(s) Capacity (kW)	500	500	500	500	500
Electric Rate/Fuel Rate (10^6 Btu basis)	1.97	1.97	1.97	1.97	1.97
System Efficiency for Power Generation (%)*	30%	23%	28%	12%	38%
Fuel Use (10^6 Btu /hr)	5.69	7.42	6.10	14.23	4.49
Useable Waste Heat (10^6 Btu /hr)	2.2	4.8	3.1	8.5	2.1
Waste Heat Temperature (F)	180 (cooling water) 800 (exhaust)	500	145	100	160
Typical Waste Heat Use	LP steam, Hot water	LP steam, Hot water	hot water	hot water	hot water
Purchased Electricity Offset (kWh)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
Electricity Cost Reduction ($/yr)	$80,550	$80,550	$80,550	$80,550	$80,550
Purchased Fuel Offset (10^6 Btu /hr)	2.2	4.8	3.1	8.5	2.1
Fuel Cost Reduction ($/yr)	$52,589	$114,739	$74,102	$204,205	$50,198
Generator Fuel Cost ($/yr)	$136,030	$177,430	$145,746	$340,074	$107,392
Installed Cost ($/kW)	$1,350	$1,500	$2,200	$2,000	$5,500
Annual Maintenance ($/yr)	$19,800	$16,200	$16,200	$18,000	$13,500
Simple Return (yr)	Never	452	Never	Never	254

*Efficiency = power output/fuel input (Btu/hr basis)

Because of the poor return on investment, CHP is not a good candidate, and is not recommended, based on the assumed operating conditions. The primary reasons that CHP is not economically feasible are (1) the high cost of natural gas relative to electricity (on a Btu basis), and (2) the relatively low annual hours available for system operation, even at 90 percent of availability. While none of the prime movers evaluated for CHP in this study showed potential, the best way to determine whether CHP will be successful is on a case-by-case basis.

Table 44 addresses the onsite distributed generation options. The prime movers considered have been reduced to those that have rapid response times and, thus, are more suitable for use in peak shaving. Note that for the CHP options, the average cost of electricity was

$0.04475/kWh; however, if $0.04475/kWh is the *average* cost of electricity, the on-peak cost will be higher. An on-peak cost of $0.080/kWh was assumed for estimation purposes, since peak shaving primarily occurs during on-peak time. Thus, the electric to fuel rate ratio is higher than for the CHP options due to the greater electricity cost during peak periods. Typical on-peak times are 10 a.m. to 10 p.m. (12 hours/day, 5days/week), which amounts to 3,000 hours per year.

Even though the electric to fuel rate ratio is greater than 3.5, the overall system efficiency is much lower than for CHP, due to the absence of heat recovery. The end result in this case is poor economic performance; the systems as evaluated are an operating expense.

Table 44. On-Site Distributed Generation Operating During Peak Hours (3,000 hr/yr)

Parameter	Reciprocating Engine	Microturbine
Generator(s) Capacity (kW)	500	500
Electric to Fuel Ratio (10^6 Btu basis)	3.53	3.53
System Efficiency for Power Generation (%)	30%	23%
Fuel Use (10^6 Btu /hr)	5.69	7.42
Purchased Electricity Offset (kWh)	1,500,000	1,500,000
Electricity Cost Reduction ($/yr)	$120,000	$120,000
Generator Fuel Cost ($/yr)	$113,358	$147,858
Installed Cost ($/kW)	$800	$800
Annual Maintenance ($/yr)	$16,500	$13,500
Simple Return (yr)	Never	Never

Because of the poor ROI, DG is not a good candidate, and is not recommended, based on the assumed operating conditions. The primary reason that DG is not economically feasible is the high cost of natural gas relative to on-peak electricity (on a Btu basis). While neither of the prime movers evaluated for DG in this study showed potential, the best way to determine whether DG can be successful is on a case-by-case basis.

ASSESSMENT OF GENERATION POTENTIAL FOR SPECIFIC FOUNDRY OPERATIONS

Exergy analysis was used to provide a basis against which the potential for power generation for the following foundry processes can be measured:

- Cupola melting furnaces
- Aluminum stack melters
- Steel casting heat treating processes
- Ductile iron pipe heat treating processes

Consideration of the quantity and temperature of the heat available from process exhaust addresses the potential for power generation based only on the physical state of the streams and is thus called “physical” exergy analysis. The composition of the exhaust is assumed to not change during energy recovery. Additionally, any particulate matter contained in the exhaust is considered inert, not contributing to or taking away from this potential.

Because the cupola exhaust is combustible, however, it is a higher quality energy source with respect to its chemical composition. Thus, to provide a complete analysis, the potential available through the chemical reactions of exhaust combustion is also considered. This is done using "chemical" exergy analysis. Chemical and physical exergy analyses are used for the evaluation of cupola exhaust for power generation. Physical exergy analysis is used on the remaining operations.

The following definitions are provided to assist in considering of the analyses presented in the subsequent sections:

- Molecular weight has units of grams/gram-mole or lb/lb-mole. One gram-mole of methane (CH_4) is equal to 16 grams of methane. Thus, the molecular weight of methane is 16 grams/gram-mole or 16 lb/lb-mole.

- The mole fraction of a species is the number of gram-moles of that species divided by the total number of gram-moles of all species in the mixture. If 20 gram-moles of methane are in 100 gram-moles of mixture, the mole fraction is 20 percent.

- The mole fraction of an ideal gas is equivalent to volume fraction. A mole fraction of 20 percent is the same as 20 percent by volume.

- The partial pressure of an ideal gas is the mole (or volume) fraction multiplied by total pressure. The total pressure is assumed to be 1 atmosphere (atm) in all calculations (1 atm = 14.7 psia).

Cupola Melting Furnace

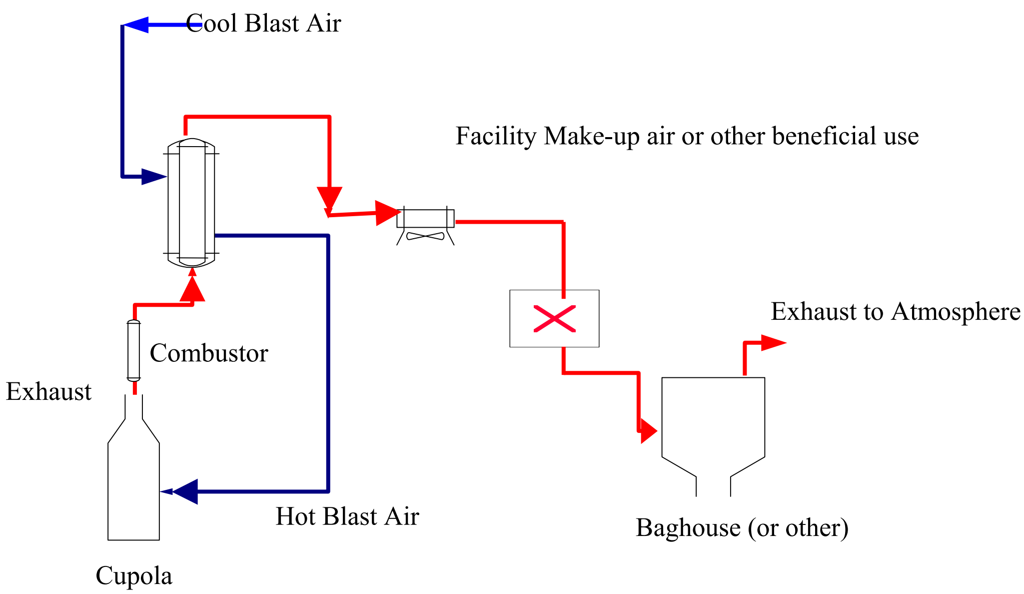
Cupola melting furnaces may be operated with coke or natural gas, but coke is most often used in production cupola operations. Exhaust from a modern, high-efficiency cupola is a combustible mixture of gases and particulate at about 500°F. The exhaust from a low-efficiency cupola contains particulate matter and about the same composition of gases, however is at a much higher temperature, usually 800°F to 850°F. Because the exhaust from high- and low-efficiency cupolas contains particulate, it is considered a "dirty" air stream. The presence of the particulate matter will pose special considerations for selection and operation of energy recovery equipment. The compositions and temperatures used in the forthcoming analyses are based on measured data from actual cupolas. As a result, the influence of particulate matter is accounted for and does not require special consideration in the analyses. [Note: The particulate matter does "contain" heat, and the potential to perform work (generate electricity) should be re-evaluated to address the consequences if the exhaust is cleaned by removal of the particulate prior to energy recovery.]

The cupola evaluated in this section is a high-efficiency unit with an output of approximately 45 tons per hour. A high-efficiency cupola was selected because it represents a limit to the potential available from the "unburned" cupola exhaust. The potential for power generation from low-efficiency cupolas may be higher. The typical composition of cupola exhaust (% by volume) before combustion is:

- Carbon monoxide (~16%);
- Carbon dioxide (~13%);
- Water vapor (~1%);
- Hydrogen (~1%); and

- Nitrogen (~69%).

Figure 29: Typical Cupola Operation (the cupola, combustor, and blast air pre-heater are shown separately)*



*EnVice LLC, Madison, WI

Many foundries have already recognized the value of combusting the relatively cool (500°F-850°F) but dirty exhaust to generate a high temperature (1,600°F) gas stream and then use the heat to preheat cupola blast air or supplement heat for other operations. Once the useful heat has been recovered, further non-beneficial cooling of the exhaust is performed before undesirable constituents are removed using a baghouse or other control technology. A typical cupola process flow diagram is shown in Figure 29. The cupola, exhaust combustor, and blast-air preheater are shown separately for illustration.

As previously discussed, recovering heat from combustion of the cupola exhaust has obvious economic benefits. This is because the heat recovered does not need to be supplied by additional coke or natural gas combustion. While it is clear that the heat from the combusted cupola exhaust has value, what is the penalty to obtain this heat? To put it another way: what potential for power generation – production of a more valuable resource – was lost by combustion of the exhaust to generate heat?

Exergy Analysis

The following sections summarize the results of the chemical and physical exergy analysis as applied to the processes identified previously. To facilitate the analysis, the following general assumptions and definitions were applied:

- All exhaust streams are ideal gases at 14.7-psia (1 atm) and the temperatures are as specified.

- The analysis of the chemical exergy (ξ_{ch}) of the cupola exhaust is based on the standard chemical exergy for a species (LHVs are not used).

- The reference state is taken to be combustion products at the standard temperature and pressure of most tables on combustion (STP; 77°F & 14.7-psia).

- The dead state is taken to be the reference state.

- $(\Delta h)_{1\rightarrow 2} = Cp_{mean} \times (T_2 - T_1)$ [=] Btu/lb*mole.

- $(\Delta s)_{1\rightarrow 2} = \{Cp_{mean} \times LN(T_2/T_1) + R \times LN(Po/P)\}$[=] Btu/lb*mole.

- The term for entropy of mixing used to determine the chemical exergy of the cupola exhaust is defined as: R x LN(Po/Pi) }[=] Btu/lb*mole, where Po is the dead state pressure of 1 atm (14.7-psia) and Pi is the partial pressure of the chemical species under consideration.

- The gas constant R is defined as: R = 1.987 Btu/(lb*mole*R).

- Steady state operation is assumed for all processes.

- Coke is $180/ton and has a heating value of 14,000 Btu/lb, which places coke at a cost of approximately $6.42/10^6 Btu.

Included in each section are tables summarizing most of the data needed to perform necessary calculations. A complete data set can be found in the appendices.

Chemical Exergy of Cupola Exhaust

The pre-combustion and post combustion stream conditions used in the analysis are shown in Tables 45 and 46, respectively. Note that Table 47 represents data for the cupola exhaust "after" combustion, as can be seen by the higher temperature of 1,600°F. This is the hot stream typically used for cupola blast air preheating.

Table 45. Cupola Pre-combustion Exhaust Stream Conditions

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (Btu/(lb-mol*F))	Partial Pressure (atm)
CO	2,484.1	0.0767	500	960	7.079	0.0767
CO_2	2,013.6	0.0622	500	960	9.909	0.0622
H_2	110.0	0.0034	500	960	6.915	0.0034
H_2O (v)	545.3	0.0168	500	960	8.271	0.0168
N_2	23,729.5	0.7328	500	960	7.036	0.7328
O_2	3,497.9	0.1080	500	960	7.315	0.1080
Totals	**32,380.5**	**1.00**				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351(30)

The results of the analysis are summarized in Table 47. Results indicate that 38 percent (4,149 kW) of the original potential to generate electricity is lost due to the combustion process. If electricity was generated during combustion, better use would be made of the chemical energy stored in the cupola exhaust. Assuming combustion could take place in a device similar to a combustion turbine with an efficiency of 30 percent, generation of 1,244 kW would be possible. Since typical combustion turbines have exhaust temperatures of 800°F to 1,000°F, there would still be thermal energy remaining for heat recovery, although supplemental firing may be required to increase the blast air temperature to its initial value.

Table 46. Cupola Post-combustion Exhaust Stream Conditions

Species	Moles/min	Mole Fraction	Temperature		Cp_{mean}* (Btu/(lb-mol*F))	Partial Pressure (atm)
			(F)	(R)		
CO_2	4,497.7	0.1510	1,600	2,060	11.67	0.1510
N_2	23,279.5	0.7967	1,600	2,060	7.405	0.7967
O_2	903.8	0.0303	1,600	2,060	7.871	0.0303
H_2O (v)	655.3	0.0220	1,600	2,060	9.060	0.0220
Totals	**29,786.3**	**1.00**				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351$_{(30)}$

The "value" estimate does not include equipment maintenance costs, which can be significant depending on the actual process installed. Considering potential maintenance costs, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on the assumed conditions.

Table 47. Results Summary - Potential Lost from Combustion of Cupola Exhaust

Exergy Lost (Btu/hr)	**Generation Potential Lost (%)**	**Power Output Lost (kW)**	**Value if 30% is Recovered ($/yr)**
14,165,671	38.0	4,149	$89,000 (a)
14,165,671	38.0	4,149	$200,000 (b)

(a) 1,600 hours per year and (b) 3,600 hours per year.

However, longer operating hours and higher electricity costs improve project economics. Also, it is important to remember that these results are for a high-efficiency cupola; a low-efficiency cupola may offer greater potential. [Note: In practice, the economics of electricity generation should be compared against the economics of heat recovery, even if power generation is the more "efficient" option. This is particularly true when there is a little difference between the cost of electricity and coke, as is the case in this analysis.]

Physical Exergy of Cupola Exhaust

Attention is now turned from generation potential lost by combustion of cupola exhaust, to the potential of electricity generation by heat recovery from the post-combustion exhaust. The post-combustion stream conditions used in the analysis are shown in Table 48, and the results of the analysis are summarized in Table 49. The analysis assumes a final temperature of 400°F, a temperature typically high enough to prevent condensation of acid gas.

Table 48. Post-combustion Stream Conditions

Species	Moles/min	Mole Fraction	Gas Discharge Temperature (F)	Gas Discharge Temperature (R)	Cp_{mean}* (Btu/(lb-mol*F))	Partial Pressure (atm)
CO_2	4,497.7	0.1510	1,600	2060	11.67	0.1510
N_2	23,729.5	0.7967	1,600	2060	7.405	0.7967
O_2	908.3	0.0303	1,600	2060	7.871	0.0303
H_2O (v)	655.3	0.0220	1,600	2060	9.060	0.0220
Totals	**29,786.3**	**1.00**				

*Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351$_{(30)}$

Table 49. Results Summary
Generation Potential from Post Combustion Cupola Exhaust

Exergy Lost (Btu/hr)	**Power Output Potential (kW)**	**Value if 16% is Recovered* ($/yr)**
23,513,708	6,887	$80,000 (a)
23,513,708	6,887	$178,000 (b)

(a) 1,600 hours per year and (b) 3,600 hours per year.

Results indicate a potential to generate 6,900 kW. Assuming the heat recovery/electricity generation process can operate at an efficiency of 16 percent of the potential value, approximately 1,100 kW of generation is possible. This efficiency is within the range of a condensing steam turbogenerator using heat recovery boilers.

Because energy is removed from the exhaust during generation, there is the potential that not enough thermal energy will remain for blast air preheating without supplemental natural gas firing. This requires consideration if this option is explored.

The "value" estimate does not include equipment maintenance costs, which can be significant depending on the actual process installed. Considering maintenance costs, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on assumed conditions. However, longer operating hours and higher electricity costs will improve project economics. [Note: In practice, the economics of electricity generation should be compared against the economics of heat recovery, even if power generation is the more "efficient" option. This is particularly true when there is little difference between the cost of electricity and coke, as is the case in this analysis.]

Aluminum Stack Melter

The aluminum stack melter exhaust has the composition of typical combustion gas, but is at an initial temperature of 400°F, a much lower temperature than cupola exhaust. This low temperature limits the potential for power generation.

The stream conditions used in the analysis are shown in Table 50, and the results of the analysis are summarized in Table 51. The "value" scenario in Table 51 assumes a recovery efficiency of 16 percent of the power output potential, which is within the efficiency range of a condensing steam turbogenerator using heat recovery boilers.

Table 50. Aluminum Stack Melter Exhaust Stream Conditions

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (Btu/(lb-mol*F))	Partial Pressure (atm)
O_2	19.2	0.0163	300	760	7.184	0.0163
N_2	792.5	0.6736	300	760	6.988	0.6736
CO_2	95.8	0.0814	300	760	9.686	0.0814
H_2O (v)	269.1	0.2287	300	760	8.154	0.2287
Totals	**1,176.6**	**1.00**				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351$_{(30)}$

Table 51. Results Summary for Aluminum Stack Melter Exhaust

Exergy Change (Btu/hr)	**Power Output Potential (kW)**	**Value if 16% is Recovered* ($/yr)**
38,795	11	$125 (a)
38,795	11	$300 (b)

(a) 1,600 hours per year and (b) 3,600 hours per year.

The results indicate that there is not enough thermal energy at a high enough temperature in aluminum stack melter exhaust for feasible power generation. Further evaluation under the assumed conditions is not recommended. Stack melters that operate at much greater temperatures, capacities, and hours of operation offer greater potential.

Steel Casting Heat Treating

The exhaust from steel casting heat treating processes is assumed to have the composition of typical combustion gas, but at a higher temperature than the exhaust from the aluminum stack melter. The stream conditions used in the analysis are shown in Table 52, and the results of the analysis are summarized in Table 53. Note that the final temperature, (T_2), is 300°F, a lower temperature limit typically selected when recovering heat from combustion gas. While it is theoretically possible to lower the temperature further and still not condense acid gases resulting from combustion, as a practical matter, it was not done intentionally.

The temperature T_1 is the initial temperature of the combustion gas; in this case, it is taken as 1,000°F. Steel casting heat treating operations typically operate at two temperature levels but at different times in the production cycle. The temperature levels in this case are 1,000°F and 1,750°F. The lower temperature was used to establish a lower limit of potential for electricity generation.

Assuming the heat recovery/electricity generation process can operate at an efficiency of 16 percent of the potential value, approximately 100 kW of power generation is possible. An efficiency of 16 percent is within the range of condensing steam turbogenerator using heat recovery boilers.

Table 52. Steel Casting Heat Treating Exhaust Stream Conditions

Species	Estimated Composition (moles)	Estimated Composition (mole fraction)	Cp_{mean} @T_1* Btu/(lb-mol*F)	Cp_{mean} @T_1* Btu/(mol*F)	Cp_{mean} @T_2* Btu/(lb-mol*F)	Cp_{mean} @T_2* Btu/(mol*F)
CO_2	118,055,898	0.082	11.78	0.025947137	9.686	0.021334802
N_2	972,024,149	0.674	7.443	0.016394273	7.011	0.015442731
O_2	23,489,651	0.016	7.909	0.017420705	7.251	0.015971366
H_2O(v)	328,832,964	0.228	9.138	0.020127753	8.211	0.018085903
Totals	**1,442,402,662**	**1.00**				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351 (30)

Table 53 Results Summary for Steel Casting Heat Treating Exhaust*

Exergy Change (Btu/hr)	**Power Output Potential (kW)**	**Value if 16% is Recovered* ($/yr)**
2,295,395	672	$8,000 (a)
2,295,395	672	$18,000 (b)

(a) 1,600 hours per year and (b) 3,600 hours per year.

The "value" estimate does not include equipment maintenance costs, which can be significant depending on the actual process installed. Considering maintenance costs, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on assumed conditions. However, longer operating hours and higher electricity costs will improve project economics. [Note: In practice, the economics of electricity generation need to be compared against the economics of heat recovery, even if power generation is the more "efficient" option. This is particularly true when there is little difference between the cost of electricity and natural gas, as is the case in this analysis.]

Ductile Iron Pipe Heat Treating

The combustion exhaust from ductile iron pipe, heat treating processes is similar in composition to that of steel casting heat treating combustion processes. However, the exhaust from the ductile iron-pipe heat treating process is 1,740°F, a much higher temperature. The stream conditions used in the analysis are shown in Table 54 and the results of the analysis are summarized in Table 55. Note that as before, the final temperature, T_2, is 300°F, a lower temperature limit typically selected when recovering heat from combustion gas. While it is theoretically possible to lower the temperature further and still not condense acid gases resulting from combustion, as a practical matter, it was not done intentionally.

Assuming the heat recovery/electricity generation process can operate at an efficiency of 16 percent of the potential value, approximately 260 kW of generation is possible. An efficiency of 16 percent is within the range of a condensing steam turbogenerator utilizing heat recovery boilers.

Table 54. Steel Casting Heat Treating Exhaust Stream Conditions

Species	Estimated Composition (moles)	(mole fraction)	Cp_{mean} @T_1* Btu/ (lb-mol*F)	Cp_{mean} @T_1* Btu/(mol*F)	Cp_{mean} @T_2* Btu/ (lb-mol*F)	Cp_{mean} @T_2* Btu/(mol*F)
CO_2	118,055,898	0.082	11.78	0.025947137	9.451	0.020817181
N_2	972,024,149	0.674	7.443	0.016394273	6.988	0.01539207
O_2	23,489,651	0.016	7.909	0.017420705	7.184	0.015823789
H_2O	328,832,964	0.228	9.138	0.020127753	8.154	0.017960352
Totals	**1,442,402,662**	**1.00**				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351 (30)

Table 55. Results Summary for Ductile Iron Pipe Heat Treating Exhaust

Exergy Change (Btu/hr)	**Power Output Potential (kW)**	**Value if 16% is Recovered ($/yr)**
5,680,970	1,664	$19,000 (a)
5,680,970	1,664	$43,000 (b)

(a) 1,600 hours per year and (b) 3,600 hours per year.

The "value" estimate does not include equipment maintenance costs, which can be significant, depending on the actual process installed. Considering maintenance, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on assumed conditions. However, longer operating hours and higher electricity costs will improve project economics.

[Note: In practice, the economics of electricity generation need to be compared against the economics of heat recovery, even if power generation is the more "efficient" option. This is particularly true when there is small difference between the cost of electricity and natural gas, as is the case in this analysis.]

CHP SUMMARY

Metalcasting and foundry operations provide the opportunity for the use of purchased fuels for combined heat and power (CHP) and onsite distributed generation (DG). The thermal (heat) and/or chemical energy stored in process waste streams also provide an opportunity to generate electricity. The use of waste energy has the advantage of being a "free" fuel, which can minimize the cost of generated electricity.

The potential for the application of CHP and DG, and the use of process waste heat was evaluated for each of the following scenarios:

- Microturbine or similar small-scale generation, with waste heat integrated into the process.
- Fuel cells with waste heat integrated into the process.
- Waste heat recovery to produce useful heat energy at a higher temperature using heat pumps.
- Waste heat chillers or absorption heat pumps for energy recovery.

- Trigeneration (combined cooling, heating, and power).

The prime movers most suitable for CHP are those that provide waste heat at a high enough temperature to be useable the greatest amount of time. Five different prime movers were considered for CHP use:

- Reciprocating engines;
- Microturbines;
- Stirling engines;
- Organic Rankine Cycle turbogenerators; and
- Phosphoric acid fuel cells.

Each of these prime movers was evaluated assuming (1) an output of 500 kW and (2) all waste heat generated is useable within a facility.

Onsite distributed generation (no heat recovery) was evaluated only for microturbines and reciprocating engines, assuming an output of 500 kW. A generator output of 500 kW was chosen because it appears to be a small enough capacity to be suitable for use in most foundries. Because of the many sources of waste energy in foundries, only four high-energy recovery potential operations were considered as candidates to evaluate the potential for generation of electricity. The four operations include:

- High-efficiency cupola melting furnaces (cast iron);
- Aluminum stack melters;
- Steel casting heat-treat processes; and
- Ductile iron pipe heat-treat processes.

The data used in the analysis of the waste energy potential represents, to the greatest extent possible, average values representative of those that would be encountered in the field. Thus, the results are general in nature and intended to serve only as a guide for potential application.

Because the "waste" energy is essentially free, there is no additional fuel cost incurred for equipment operation unless supplemental firing is required, although maintenance costs also merit consideration. Examples of electricity generation from waste energy are the use of (1) high-quality (temperature) heat to generate steam to drive a steam turbogenerator, or (2) lower grade waste heat (400°F to 500°F) to drive an Organic Rankine Cycle (ORC) turbogenerator.

To allow estimation of the economic potential, the following utility rates were assumed:

- Natural gas is $6.63/$10^6$ Btu.

- Coke is $180/ton ($6.42/10^6 Btu).

- Electricity is $0.04475/kWh, on average.

- Electricity is $0.080/kWh during on-peak time.

- Operating hours are based on a 16-hour, 5-day workweek, 50 weeks per year. Since the processes under consideration may have widely varying operating hours at any given facility, benefits are shown based on 40 percent and 90 percent availability during operating hours.

CHP

None of the prime movers evaluated for CHP using purchased fuels show reasonable potential for success, and are not recommended for consideration under the assumed conditions. ROIs were either found to be greater than 100 years, or the systems would actually be an operating expense. The primary reasons that CHP is not economically feasible are (1) the high cost of natural gas relative to electricity (on a Btu basis), and (2) the relatively low annual hours available for system operation, even at 90 percent availability. While none of the prime movers evaluated for CHP in this study showed potential, the best way to determine whether CHP will be successful is on a case-by-case basis.

Onsite Distributed Generation (DG)

None of the prime movers evaluated for DG using purchased fuels show reasonable potential for success; thus, DG is not recommended for consideration under the assumed conditions. The primary reason that DG is not economically feasible is the high cost of natural gas relative to on-peak electricity (Btu basis). While neither of the prime movers evaluated for DG in this study shows potential, the best way to determine whether DG can be successful is on a case-by-case basis.

Heat Recovery – Use of Thermally-Activated Chiller

Thermal chillers use a heat source to produce a desired cooling effect. When the cost of purchased fuels is low or a waste heat source is available, thermal chillers can offer relatively low cost cooling. The foundry industry does not, however, appear to have a large-scale need for refrigerated cooling, and related options are not likely to be economically feasible on the basis of energy alone. However, there may be other economic benefits. For example, if the availability of a constant, low-temperature source reduces product cool down time, increases in production rate may result. Because of the potential benefit, it is recommended that thermal chillers be considered in those cases where refrigerated chilling is in place, or when other benefits may result. Information was included for those who wish to consider thermal chillers.

Heat Recovery—Heat Pump

A heat pump moves energy from a source at a lower temperature to meet heat load requirements at another temperature. There are several different types of heat pumps typically used in industrial settings. While the low, upper temperature capability of 200°F to 250°F will likely limit use in foundries or metalcasting operations, it is recommended that heat pumps be considered in those cases where lower temperatures are involved. There are several potential heat pump applications in a foundry:

- Dehumidification of blast air (prior to heating) and use of the reject heat for preheating of combustion air for the cupola or other furnace.

- Dehumidification and cooling of sand cooler air, with use of reject heat for other adjacent applications that require heating.

- Controlling humidity in metal scrap storage areas to prevent metal oxidation.

- Space heating for office or plant areas.

Some basic information on heat pumps was included for informational purposes.

High-Efficiency Cupola Melting Furnace (cast iron)

The cupola furnace showed by far the greatest potential of the four process operations considered. The high-efficiency cupola was the only one considered because of the significant advantages of converting low-efficiency cupolas to high-efficiency designs. To determine power generation potential, two scenarios were evaluated:

1. The power generation potential lost due to combustion of exhaust for blast air preheating; and

2. The power generation potential of the hot gas after combustion, but before blast air preheating.

1. Power generation potential lost due to combustion of cupola exhaust
Application of exergy analysis indicated that during combustion of the cupola exhaust for preheating blast air, approximately 38 percent of the potential to generate electricity, or 4,200 kW, is lost. This lost generation potential cannot be regained by heat recovery. Thus, the value in terms of electricity is gone as well. However, assuming that a combustion turbine with an efficiency of 30 percent is used to generate electricity during combustion of the cupola exhaust, the generation potential is approximately 1,200 kW.

Combustion of the cupola exhaust for power generation makes less thermal energy available for blast air preheating. Since typical combustion turbines have exhaust temperatures of 800°F to 1,000°F, it may be necessary to use supplemental firing with natural gas or another fuel to elevate blast air to the desired temperature. Considering potential maintenance costs and the low cost of electricity, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on the assumed conditions. However, longer operating hours and higher electricity cost will improve project economics.

2. Power generation potential of the hot cupola exhaust after combustion
Application of exergy analysis indicates that the potential for power generation from the hot cupola exhaust is approximately 6,900 kW. However, assuming that the heat recovery/generation process efficiency is 16 percent, the generation potential is approximately 1,100 kW.

Considering potential maintenance costs and the low cost of electricity, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on the assumed conditions. However, longer operating hours and higher electricity will improve project economics.

Aluminum Stack Melter Exhaust

The low temperature of the aluminum stack melter exhaust (400°F) makes this a poor candidate for power generation using waste heat recovery. The theoretical potential was estimated at 11 kW. This option is not recommended for further consideration, based on the assumed conditions. The stack melter was the only furnace considered because of the significant energy reduction potential of upgrading other furnace designs to this technology.

Steel Casting Heat Treating

At an exhaust temperature of 1,000°F, the steel casting heat treating exhaust shows a theoretical potential of approximately 670 kW, with a realistic potential of approximately 100 kW, assuming a heat recovery/generation efficiency of 16 percent. However, the temperature of the exhaust is at 1,000°F for part of the time and at 1,750°F for the remainder of operating hours. Depending on actual temperature, the potential may be higher.

Considering potential maintenance costs and the low cost of electricity, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on the assumed conditions. However, longer operating hours and higher electricity costs will improve project economics.

Ductile Iron Pipe Heat Treating

At an exhaust temperature of 1,740°F, the ductile iron pipe heat-treat exhaust shows a theoretical potential of approximately 1,700 kW. The realistic potential is approximately 260 kW assuming a heat recovery/generation efficiency of 16 percent.

Considering potential maintenance costs and the low cost of electricity, this option does not appear to have a reasonable potential for financial return, and is not recommended, based on the assumed conditions. However, longer operating hours and higher electricity cost will improve project economics.

GLOSSARY OF TERMS

Absorption Chiller: An absorption chiller uses heat instead of mechanical energy to provide cooling. A thermal compressor consists of an absorber, a generator, a pump, and a throttling device, and replaces the mechanical vapor compressor. In the chiller, refrigerant vapor from the evaporator is absorbed by a solution mixture in the absorber. This solution is then pumped to the generator, where the refrigerant re-vaporizes using a waste steam heat source. The refrigerant-depleted solution then returns to the absorber via a throttling device. The two most common refrigerant/absorbent mixtures used in absorption chillers are water/lithium bromide and ammonia/water.

Adsorption Chiller: An adsorption chiller uses heat instead of mechanical energy to provide cooling. Instead of circulating a liquid-absorbent-medium, solid adsorbents (i.e. desiccant) are employed in components that switch function with time. First, they adsorb refrigerant from an evaporator and reject heat to the environment until filled to capacity. In a second step they are heated to drive off the refrigerant, which goes to a condenser for reuse until fully regenerated. In these systems, the solution pump is replaced with a set of switching valves.

Best Practice: In this report, the term is defined to be the achievable state of operation in a facility with the best current technology.

Coefficient of Performance (COP): COP is the ratio of the rate of heat rejection (for refrigeration) or heat supply (for heat pump) to the rate of energy input in consistent units. COP is used to measure the efficiency of refrigeration cycles and heat pump cycles.

Coke (coal): A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous, and has a heating value of approximately 26.0 million Btu per ton.

Combined Heat and Power (CHP): A plant designed to produce both heat and electricity from a single heat source.

Distributed Generation (DG): Distributed generation is any small-scale power generation technology that provides electric power at a site closer to customers than central station generation. A distributed power unit can be connected directly to the consumer or to a utility's transmission or distribution system.

Exergy: Maximum theoretical work obtainable as a system interacts with the environment to equilibrium.

Fuel Cell: A device capable of generating an electrical current by converting the chemical energy of a fuel (e.g. hydrogen) directly into electrical energy. Fuel cells differ from conventional electrical cells in that the active materials such as fuel and oxygen are not contained within the cell, but are supplied from outside. It does not contain an intermediate heat cycle, as do most other electrical generation techniques.

Heat Pump: Heating and/or cooling equipment that draws heat into a building from outside during the heating season and ejects heat from the building to the outside during the cooling season. Heat pumps are vapor-compression refrigeration systems whose indoor/outdoor coils are used reversibly as condensers or evaporators, depending on the need for heating or cooling.

Hysteresis: The phenomenon of lost energy that occurs during any cycle of loading or unloading when a material is subject to repeated loading.

Industry Average Energy Use: A baseline of current foundry energy usage based on the best available information.

Microturbine: A centrifugal generator that operates in a similar fashion to a combustion turbine, except that the turbine rotor spins at a much higher speed. Microturbines use organic fuels, such as fuel oil, propane, or natural gas. A single unit can be configured to operate on more than one fuel to allow for switching capability.

Onsite Energy: Onsite energy is the energy used within a facility. This is sometimes called "primary energy." Electrical onsite energy is the kilowatt hours used and does not include the "secondary energy" required for generation and transmission of electricity.

Organic Rankine Cycle Turbogenerator: An Organic Rankine Cycle Turbogenerator operates similarly to the Rankine Cycle of a conventional steam turbine, except for the fluid that drives the turbine, which is a high molecular mass organic fluid. The selected working fluids are allowed to efficiently exploit low-temperature heat sources to produce electricity in a wide range of power outputs (from few kW up to 3 MW electric power per unit).

Reciprocating Engine: An internal-combustion engine in which the crankshaft is turned by pistons moving up and down in cylinders.

Recuperative Heat Exchanger: A piece of equipment that transfers heat continuously through stationary heat transfer surfaces that separates the hot flow stream from the cold flow stream.

Steam Turbogenerator: A steam turbine accepts steam from an external source, such as a heat recovery boiler or natural gas-fired boiler. Heat recovery boilers use waste thermal energy to generate steam. Regardless of how the steam is generated, a turbine expands steam from a higher pressure and temperature to a lower pressure and temperature. During expansion of the steam, the turbine imparts power to a shaft that is used to turn a generator for production of electricity.

Sterling Engine: An external combustion engine that converts heat into useable mechanical energy (shaftwork) by the heating (expanding) and cooling (contracting) of a captive gas such as helium or hydrogen.

Tacit Energy: A term used to describe an energy value that equals the combination of onsite energy consumption, the process energy required to produce and transmit/transport the energy source, and feedstock energy.

Theoretical Minimum: Theoretical Minimum (for melting) is the energy difference between the total energy content (enthalpy) of metal at typical tapping temperatures and the total energy content (enthalpy) at ambient temperatures. It is the absolute minimum amount of energy required for melting metal.

Thermal Chiller: A thermal chiller is a thermally-activated chiller (incl. both absorption and adsorption chillers).

Trigeneration: Power generation with simultaneous heating and cooling.

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APPENDIX “A”

Exhibit A1 - Cast Iron Foundry Energy Use per Shipped Ton*

Process Type	Iron Type	Electrical Btu(10^5)/Ton	Natural Gas Btu(10^5)/Ton	Oxygen Equivalent Btu(10^5)/Ton**	Coke Btu(10^5)/Ton	Total Btu(10^5)/Ton	Total Tacit Btu(10^6)/Ton
Cupola**	Gray Iron	20.68	23.69	0.47	51.00	95.84	14.56
Cupola, Greensand Molding	Gray Iron	13.87	10.69	1.25	38.43	64.24	9.98
Cupola, Greensand Molding	Gray & Ductile	17.88	11.48	0.7	43.15	73.21	11.65
		17.48	15.29	0.81	44.19	77.76	12.06
Cupola Greensand Automotive	Gray & Ductile	30.24	49.17	0.89	53.31	133.61	20.55
Gray Iron Cupola Average		23.86	32.23	0.85	48.75	105.69	16.31
Induction**	Gray Iron	117.97	58.9			176.87	43.05
GI Average* **		**70.91**	**45.56**	**0.42**	**24.38**	**141.28**	**29.68**
Cupola**	Ductile Iron	22.25	20.21	0.08	58.72	101.26	15.40
Cupola**, Centrifugal	Ductile Pipe	4.58	26.48	0.89	27.87	59.82	7.43
Cupola, Centrifugal	Ductile Pipe	5.83	31.17	0.89	27.37	65.40	8.25
Ductile Pipe Avg.		**5.21**	**28.83**	**0.89**	**27.62**	**62.61**	**7.84**
Induction**	Ductile Iron	85.43	59.70			145.13	32.92
Induction Greensand Molding	Ductile-D	54.29	18.01			72.30	18.88
Induction Greensand Molding	Ductile-D	55.93	16.24			72.17	19.21
Ductile-D Average		55.11	17.13			72.24	19.05
Ductile Average		**70.27**	**38.41**			**108.68**	**25.99**

*"Oxygen Equivalent" is an estimate of the amount of electricity used to produce the oxygen delivered to the site and not actual electricity used by the

** Participated in "Energy Use in Selected Metal Casting Facilities", DOE, 2003(2). Others facilities did not directly participate in the study.

*** Cupola melt shops shipments at 62% and Induction Melt 38% per modified numbers from EPA-453/R-2-013.

Exhibit A2 - Steel Foundry Energy Use per Shipped Ton*

Process	Electrical Btu(10^5)/Ton	Natural Gas Btu(10^5)/Ton	Oxygen Equivalent Btu(10^5)/Ton*	Total Btu(10^5)/Ton	Total Tacit Btu(10^6)/Ton
Induction Melt, Stainless, Airset Molding**	224.2	267.2	0	491.4	97.75
Arc Melt, Low Carbon, Greensand and Airset**	92.2	114.8	0	207	40.70
Induction Melt, Low Carbon, Airset**	68.9	103.6	0	172.5	32.24
Average Steel (Used only Low Carbon)	**80.55**	**109.20**	**0.00**	**189.75**	**36.47**

Exhibit A3 - Aluminum Casting Energy Use per Shipped Ton*

Process	Electrical Btu(10^5)/Ton	Natural Gas Btu(10^5)/Ton	Oxygen Equivalent Btu(10^5)/Ton*	Total Btu(10^5)/Ton	Total Tacit Btu(10^6)/Ton
High Pressure Die Casting**	66.01	252.80	0.00	318.81	46.65
High Pressure Die Casting, Automotive**	199.20	116.83	0.00	316.03	74.48
High Pressure Die Casting Average	**132.61**	**184.82**	0.00	**317.42**	**60.56**
Permanent Mold, Sand Casting**	**121.22**	**597.84**	0.00	**719.06**	**99.36**
Lost Foam, Automotive**	188.41	552.20	0.00	740.61	115.76
Adjusted Lost Foam, Automotive	188.41	313.48	0.00	501.89	91.27
Estimated non-Automotive Lost Foam	176.93	210.92	0.00	387.84	77.14
Lost Foam Average	**180.75**	**245.10**	0.00	**425.86**	**81.85**

*"Oxygen Equivilant" is an estimate of the amount of electricity used to produce the oxygen delivered to the site and not actual electricity used by the foundry listed in this report. Small amounts of propane and fuel oil are included in the total but not broken out individually. Steel Foundry oxygen usage not available for the energy analysis.

** Participated in "Energy Use in Selected Metal Casting Facilities", DOE, 2003$_{(2)}$. Others facilities did not directly participate in the study.

Note: Diecast considered representative of die cast, permanent, and investment. Permanent Mold/Sand considered representative of sand.

Appendix A4 - Magnesium Die Cast Energy Use per Shipped Ton*

Process	Electrical $Btu(10^5)/Ton$	Natural Gas $Btu(10^5)/Ton$	Oxygen Equivalent $Btu(10^5)/Ton*$	Total $Btu(10^5)/Ton$	Total Tacit $Btu(10^6)/Ton$
Electric Melt, High Pressure Die Casting**	206.16	48.66	0.00	254.82	69.67
Electric Melt, High Pressure Die Casting**	186.44	71.92	0.00	258.36	65.87
Electric Melt, High Pressure Die Casting Average	**196.30**	**60.29**	**0.00**	**256.59**	**67.77**

Appendix A5 - Zinc Die Cast Energy Use per Shipped Ton*

Process	Electrical $Btu(10^5)/Ton$	Natural Gas $Btu(10^5)/Ton$	Oxygen Equivalent $Btu(10^5)/Ton*$	Total $Btu(10^5)/Ton$	Total Tacit $Btu(10^6)/Ton$
Gas/Electric, Hot Chamber Die Casting**	**42.04**	**99.08**	**0.00**	**141.12**	**23.35**

Appendix A6 - Copper Based Foundry Energy Use per Shipped Ton*

Process	Electrical $Btu(10^5)/Ton$	Natural Gas $Btu(10^5)/Ton$	Oxygen Equivalent $Btu(10^5)/Ton*$	Total $Btu(10^5)/Ton$	Total Tacit $Btu(10^6)/Ton$
Induction Melting, Sand Molding**	82.26	24.54	0.00	106.80	28.32
Induction Melting, Sand Molding**	128.68	57.88	0.00	186.56	46.31
Induction Melting, Sand Molding Average	**105.47**	**41.21**	**0.00**	**146.68**	**37.32**

*"Oxygen Equivilant" is an estimate of the amount of electricity used to produce the oxygen delivered to the site and not actual electricity used by the foundry listed in this report. Small amounts of propane and fuel oil are included in the total but not broken out individually.

** Participated in "Energy Use in Selected Metal Casting Facilities", DOE, 2003(2).

Appendix A7 - Cast Iron Tacit Energy Usage by Type and CO_2 Emissions*

Cast Iron Alloy	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
GI Average					
Btu(10^6) per Shipped Ton	7.09	4.56	0.04	2.44	14.13
Tacit Btu(10^6) per Shipped Ton	22.25	4.68	0.13	2.63	29.68
Tons CO_2 per Shipped Ton					2.02
Est. 2003 Tacit Btu(10^{12})	121.86	25.61	0.73	14.38	162.58
****Est. 2003 CO_2 Emissions, Tons(10^3)**					11,187
Ductile Pipe Average					
Btu(10^6) per Shipped Ton	0.52	2.88	0.09	2.76	6.25
Tacit Btu(10^6) per Shipped Ton	1.63	2.96	0.28	2.97	7.84
Tons CO_2 per Shipped Ton					0.56
Est. 2003 Tacit Btu(10^{12})	3.27	5.91	0.56	5.95	15.69
****Est. 2003 CO_2 Emissions, Tons(10^3)**					1,160
Ductile Average (without Pipe)					
Btu(10^6) per Shipped Ton	7.03	3.84	0.00	0.00	10.87
Tacit Btu(10^6) per Shipped Ton	22.04	3.94	0.00	0.00	25.99
Tons CO_2 per Shipped Ton					1.73
Est. 2003 Tacit Btu(10^{12})	44.44	7.95	0.00	0.00	52.39
****Est. 2003 CO_2 Emissions, Tons(10^3)**					3,494
Summary					
Est. 2003 Total Tacit Btu(10^{12}) per Year	169.57	39.47	1.29	20.33	231
Est. 2003 Total CO_2 Emissions, Tons(10^3)					15,841
Average Emissions, CO_2 (Tons/Shipped Ton)					**1.65**

***Key Conversion Factors Used in Calculating Energy Usage**

Energy Form	Energy Content	Unit	Tacit Energy	Unit
Coke	13,000	Btu/lb	14,000	Btu/lb
Electricity	3,412	Btu/kWh	10,500	Btu/kWh
Natural Gas	1,000	Btu/scf	1,026	Btu/scf
Oxygen	61	Btu/scf	175	Btu/scf

****Estimated 2003 Shipped Tons**

Cast Iron	Shipped Tons
Gray Iron	5,477,808
Ductile Iron	2,000,000
Ductile Average (without Pipe)	2,016,128

Appendix A8 - Aluminum Tacit Energy Usage by Type and CO_2 Emissions*

Aluminum Process	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
High Pressure Die Casting					
Btu(10^6) per Shipped Ton	13.26	18.48	0.00	0.00	31.74
Tacit Btu(10^6) per Shipped Ton	41.60	18.96	0.00	0.00	60.56
Tons CO_2 per Shipped Ton					3.95
Est. 2003 Tacit Btu(10^{12})	65.96	30.07	0.00	0.00	96.03
****Est. 2003 CO_2 Emissions, Tons(10^3)**					6,217
Permanent Mold/Sand					
Btu(10^6) per Shipped Ton	12.12	59.78	0.00	0.00	71.91
Tacit Btu(10^6) per Shipped Ton	38.02	61.34	0.00	0.00	99.36
Tons CO_2 per Shipped Ton					3.70
Est. 2003 Tacit Btu(10^{12})	14.19	7.08	0.00	0.00	21.27
****Est. 2003 CO_2 Emissions, Tons(10^3)**					1,372
Lost Foam					
Btu(10^6) per Shipped Ton	18.08	24.51	0.00	0.00	42.59
Tacit Btu(10^6) per Shipped Ton	56.70	25.15	0.00	0.00	81.85
Tons CO_2 per Shipped Ton					5.34
Est. 2003 Tacit Btu(10^{12})	17.24	7.65	0.00	0.00	24.88
****Est. 2003 CO_2 Emissions, Tons(10^3)**					1,613
Summary					
Est. 2003 Total Tacit Btu(10^{12}) per Year	97.39	44.79	0.00	0.00	142
Est. 2003 Total CO_2 Emissions, Tons(10^3)					9,202
Average Emissions, CO_2 (Tons/Shipped Ton)					**4.07**

*Estimated 2003 Shipped Tons	
Alloy	**Shipped Tons**
HP Die Casting	1,585,720
Permanent Mold/Sand	373,266
Lost Foam	304,014

Appendix A9 - Steel Tacit Energy Usage by Type and CO_2 Emissions*

Steel	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
All Steel Casting					
Btu(10^6) per Shipped Ton	8.06	10.92	0.00	0.00	18.98
Tacit Btu(10^6) per Shipped Ton	25.27	11.20	0.00	0.00	36.47
Tons CO_2 per Shipped Ton					2.38
Est. 2003 Tacit Btu(10^{12})	31.78	14.09	0.00	0.00	45.87
****Est. 2003 CO_2 Emissions, Tons(10^3)**					2,993
Average Emissions, CO_2 (Tons/Shipped Ton)					**2.38**

*Estimated 2003 Shipped Tons	
Alloy	**Shipped Tons**
Steel	1,257,660

Appendix A10 - Magnesium Tacit Energy Usage by Type and CO_2 Emissions*

Magnesium	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
All Magnesium Casting					
Btu(10^6) per Shipped Ton	19.63	6.03	0.00	0.00	25.66
Tacit Btu(10^6) per Shipped Ton	61.58	6.19	0.00	0.00	67.77
Tons CO_2 per Shipped Ton					4.56
Est. 2003 Tacit Btu(10^{12})	6.56	0.66	0.00	0.00	7
****Est. 2003 CO_2 Emissions, Tons(10^3)**					486
Average Emissions, CO_2 (Tons/Shipped Ton)					**4.56**

*Estimated 2003 Shipped Tons	
Alloy	**Shipped Tons**
Magnesium	106,600

Appendix A11 - Zinc Tacit Energy Usage by Type and CO_2 Emissions*

Zinc	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
All Zinc Casting					
Btu(10^6) per Shipped Ton	4.20	9.91	0.00	0.00	14.11
Tacit Btu(10^6) per Shipped Ton	13.19	10.17	0.00	0.00	23.35
Tons CO_2 per Shipped Ton					1.50
Est. 2003 Tacit Btu(10^{12})	4.54	3.50	0.00	0.00	8
****Est. 2003 CO_2 Emissions, Tons(10^3)**					515
Average Emissions, CO_2 (Tons/Shipped Ton)					**1.50**

*Estimated 2003 Shipped Tons	
Alloy	**Shipped Tons**
Zinc	344,000

Appendix A12 - Copper Tacit Energy Usage by Type and CO_2 Emissions*

Copper	Electrical	Natural Gas	Oxygen Equivalent	Coke	Total
All Copper Casting					
Btu(10^6) per Shipped Ton	10.55	4.12	0.00	0.00	14.67
Tacit Btu(10^6) per Shipped Ton	33.09	4.23	0.00	0.00	37.32
Tons CO_2 per Shipped Ton					2.50
Est. 2003 Tacit Btu(10^{12})	10.31	1.32	0.00	0.00	12
****Est. 2003 CO_2 Emissions, Tons(10^3)**					780
Average Emissions, CO_2 (Tons/Shipped Ton)					**2.50**

*Estimated 2003 Shipped Tons	
Alloy	**Shipped Tons**
Copper	311,600

APPENDIX “B”

EXHIBIT B1

Power Generation Potential Lost Due to Cupola Exhaust Combustion

$CO + H_2 + O_2$ ----> $CO_2 + H_2O$

Uncombusted Cupola Exhaust (fuel) 12,985 scfm (68 F)
Mole Flow of Cupola Exhaust 15,277.6 mol/min

Cupola Exhaust Stream Composition Analysis

Uncombusted Cupola Exhaust			Combustion Air (stoichiometric)*			Combusted Cupola Exhaust		
Species	**Mole Fraction**	**Moles/min**	**Species**	**Moles/min**	**Mole Fraction**	**Species**	**Moles/min**	**Mole Fraction**
CO	0.1626	2,484.1	O_2	2,594.1	0.2100	CO_2	4,497.7	0.1510
CO_2	0.1318	2,013.6	N_2	9,758.9	0.7900	N_2	22,729.5	0.7967
N_2	0.6919	10,570.6				O_2	903.8	0.0303
$H_2O(v)$	0.0065	99.3	Air	12,353.1		$H_2O(v)$	655.3	0.0220
H_2	0.0072	110.0			----	Excess Air	4,303.8	----
Totals	**1.00**		**Totals**	**12,353.1**	**1.00**	**Totals**	**29,786.3**	**1.00**

*Water in air due to humidity not indicated.

Excess Air 34.8%
Exhaust Temperature (T_1) 500 (F; pre-combustion)
Exhaust Temperature (T_2) 1,600 (F; post combustion)
Gas Constant (R) 1.987 BTU/(lb-mol*R)
Total Pressure 1 atm (inlet and outlet)

EXHIBIT B1 (Continued)

Cupola Exhaust - Precombustion Stream Data

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (BTU/(lb-mole*F))	Partial Pressure (atm)	Standard Exergy (BTU/lb-mole)	Exergy Change on Mixing (BTU/lb-mole)	Exergy (BTU/hr)
CO	2,484.1	0.0767	500	960	7.079	0.0767	110,614	-1,944.5	35,676,155.0
CO_2	2,013.6	0.0622	500	960	9.909	0.0622	0	-1,852.2	-492,903.7
H_2	110.0	0.0034	500	960	6.915	0.0034	102,042	-5,282.7	1,406,619.1
H_2O (v)	545.3	0.0168	500	960	8.271	0.0168	3,697	-3,426.4	19,518.5
N_2	23,729.5	0.7328	500	960	7.036	0.7328	0	454.3	1,424,727.8
O_2	3,497.9	0.1080	500	960	7.315	0.1080	0	-1,553.6	-718,204.8
Totals	**32,380.5**	**1.00**							**37,315,912**

Cupola Exhaust - Post Combustion Stream Data

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (BTU/(lb-mol*F))	Partial Pressure (atm)	Standard Exergy (BTU/lb-mol)	Exergy Change on Mixing (BTU/lb-mol)	Exergy (BTU/hr)
CO_2	4,497.7	0.1510	1,600	2,060	11.67	0.1510	0	7,350.2	4,369,077
N_2	23,729.5	0.7967	1,600	2,060	7.405	0.7967	0	5,699.4	17,873,735
O_2	903.8	0.0303	1,600	2,060	7.871	0.0303	0	2,592.9	309,715
H_2O (v)	655.3	0.0220	1,600	2,060	9.060	0.0220	3,697	3,204.5	597,714
Totals	**29,786.3**	**1.00**							**23,150,240**

Exergy Analysis Results		
Exergy Change BTU/(hr)	**Generation Potential Lost** (%)	**Power Potential Lost** (kW)
-14,165,671.4	38.0%	4,149

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351

EXHIBIT B2

Power Generation Potential for Hot Cupola Exhaust

Uncombusted Cupola Exhaust (fuel)	12,985	scfm (68 F)
Mole Flow of Cupola Exhaust	15,277.6	mol/min

Cupola Exhaust Stream Composition Analysis								
Uncombusted Cupola Exhaust			Combustion Air (stoichiometric)*			Combusted Cupola Exhaust		
Species	**Mole Fraction**	**Moles/min**	**Species**	**Moles/min**	**Mole Fraction**	**Species**	**Moles/min**	**Mole Fraction**
CO	0.1626	2,484.1	O_2	2,594.1	0.2100	CO_2	4,497.7	0.1510
CO_2	0.1318	2,013.6	N_2	9,758.9	0.7900	N_2	23,729.5	0.7967
N_2	0.6919	10,570.6				O_2	903.8	0.0303
H_2O	0.0065	99.3	Air	12,353.1		H_2O	655.3	0.0220
H_2	0.0072	110.0			----	Excess Air	4,303.8	----
Totals	**1.00**		**Totals**	**12,353.1**	**1.00**	**Totals**	**29,786.3**	**1.00**

.

Excess Air	34.8%	
Exhaust Temperature (T_1)	2,059	(R [1,600 F]; pre-combustion)
Exhaust Temperature (T_2)	see tables below	(F; post combustion)
Gas Constant (R)	1.987	BTU/(lb-mol*R)
Total Pressure	1	atm (inlet and outlet)

EXHIBIT B2, (Continued)

Cupola Exhaust - Post Combustion Stream Data (Initial Temperature = 1,600 F)

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (BTU/(lb-mol*F))	Partial Pressure (atm)	Exergy Change (BTU/lb-mol)	Exergy (BTU/hr)
CO_2	4,497.7	0.1510	1,600	2,060	11.67	0.1510	9,363.6	5,565,880
N_2	23,729.5	0.7967	1,600	2,060	7.405	0.7967	5,941.5	18,633,016
O_2	903.8	0.0303	1,600	2,060	7.871	0.0303	6,315.4	754,348
H_2O (v)	655.3	0.0220	1,600	2,060	9.060	0.0220	7,269.5	629,560
Totals	**29,786.3**	**1.00**						**25,582,804**

Cupola Exhaust - Post Combustion Stream Data (Final Temperature = 400 F)

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (BTU/(lb-mol*F))	Partial Pressure (atm)	Exergy Change (BTU/lb-mol)	Exergy (BTU/hr)
CO_2	4,497.7	0.1510	400	860	9.686	0.1510	683.6	406,365
N_2	22,727.0	0.7630	400	860	7.011	0.7967	494.8	1,551,839
O_2	1,876.5	0.0630	400	860	7.251	0.0303	511.8	61,129
H_2O (v)	655.3	0.0220	400	860	8.211	0.0220	579.8	50,190
Totals	**29,786.3**	**1.00**						**2,069,523**

- Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351

Exergy Analysis Results		
Temperature	**Generation Potential**	
(F)	(BTU/hr)	(kW)
400	23,537,708	6,887

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351

EXHIBIT B3

Power Generation Potential for Aluminum Stack Melter Exhaust

$CH_4 + 2\ O_2$ ----> $CO_2 + 2\ H_2O$

Basis (mole Fuel @ STP):	1.0	(68 F, 14.7 psia)
Production Rate	3,000	lb/hr
Exhaust Flowrate	1,000	scfm (68 F)
Mole Flow Exhaust	1,176.6	mol/min
Exhaust Temperature	859	R (400 F)
Excess Air	10%	
Relative Humidity	50%	(at 55 F on average)

Exhaust Stream Composition Analysis

Typical Fuel / Air Composition to Burner			Basis Exhaust Composition		
Species	**Moles/min**	**Mole Fraction**	**Species**	**Moles/min**	**Mole Fraction**
CH_4	1.00	0.0814	O_2	0.20	0.0163
O_2	2.20	0.1791	CO_2	1.00	0.0814
N_2	8.28	0.6736	N_2	8.28	0.6736
H_2O (v)	0.81	0.0659	H_2O (v)	2.81	0.2287
Totals	12.29	1.00	**Totals**	12.3	1.00

Cupola Exhaust - Post Combustion Stream Data (Final Temperature = 300 F)

Species	Moles/min	Mole Fraction	Temperature (F)	Temperature (R)	Cp_{mean}* (BTU/(lb-mole*F))	Partial Pressure (atm)	Exergy Change (BTU/lb-mole)	Exergy Change (BTU/hr)
O_2	19.2	0.0163	300	760	7.184	0.0163	-239.7	-607
N_2	792.5	0.6736	300	760	6.988	0.6736	-233.2	-24,422
CO_2	95.8	0.0814	300	760	9.686	0.0814	-323.2	-4,090
H_2O (v)	269.1	0.2287	300	760	8.154	0.2287	-272.1	-9,676
Totals	**1,176.6**	**1.00**						**-38,795**

Exergy Analysis Results

Temperature	Generation Potential	
(F)	(BTU/hr)	(kW)
300	38,795	11

EXHIBIT B4

Steel Casting Heat Treating

$CH_4 + 2\ O_2 \text{ ---->}\ CO_2 + 2\ H_2O$

$C_2H_6 + 3.5\ O_2 \text{ ---->}\ 2\ CO_2 + 3\ H_2O$

$CH_4 + C_2H_6 + 5.5\ O_2 \text{ ---->}\ 3\ CO_2 + 5\ H_2O$

Fuel Higher Heat Value	1,011	BTU/cf	
Fuel Composition (estimated):	*CH_4*	*97.8%*	vol/vol
	C_2H_6	*2.1%*	vol/vol
Basis (mole Fuel @ STP):	1.0	(68 F, 14.7 psia)	
Percent Excess Air:	10.0%		
Annual Natural Gas Consumption	100,000	Mcf	
Exhaust Temperature (T_1)	1,000	degrees F	
Exhaust Temperature (T_2)	300	degrees F	(assumed minimum practical)
Air to Fuel Ratio:	9.44	cf air/cf fuel	
Annual Operating Hours:	4,000	16 hr/d, 5d/wk, 50 wk/yr	

Heat Treat Inlet Fuel / Air Stream Data

Species	Stoichiometric Composition		Estimated Composition		Totals	
	(moles)	(mole fraction)	(moles)	(mole fraction)	(moles)	(mole fraction)
CH_4	0.978	0.086	0.978	0.0841	113,194,773	0.0785
C_2H_6	0.021	0.002	0.021	0.0018	2,430,563	0.0017
O_2	2.030	0.178	2.232	0.192	258,386,166	0.179
N_2	7.635	0.669	8.398	0.722	972,024,149	0.674
Air	9.664	----	10.631	----	1,230,410,315	----
$H_2O(v)$	0.747	.0065	0.822	0.066	95,151,731	0.066
Totals	11.41	1.00	12.45	1.00	1,441,187,381	1.00

EXHIBIT B4 (Continued)

Heat Treat Exhaust Stream Data (assumes complete fuel combustion)

Species	**Estimated Composition** (moles)	(mole fraction)	**Cp_{mean} @T_1*** BTU/(lb-mole*F)	**Cp_{mean} @T_1*** BTU/(mole*F)	**Cp_{mean} @T_2*** BTU/(lb-mole*F)	**Cp_{mean} @T_2*** BTU/(mole*F)
CO_2	118,055,898	0.082	11.78	0.025947137	9.686	0.021334802
N_2	972,024,149	0.674	7.443	0.016394273	7.011	0.015442731
O_2	23,489,651	0.016	7.909	0.017420705	7.251	0.015971366
H_2O(v)	328,832,964	0.228	9.138	0.020127753	8.211	0.018085903
Totals	1,442,402,662	1.000				

* Richard Felder, Ronald Rousseau, Elementary Principles of Chemical Processes, 2nd Edition, p351.

Results Summary

Enthalpy @ T_1 BTU/(mol)	**Enthalpy @ T_2** BTU/(mol)	**Entropy @ T_1** (BTU/mol*R)	**Entropy @ T_2** (BTU/(mol*R))	**Exergy** (BTU/mol)	**Exergy** (BTU/hr)	**Exergy** (kW)
16.7	3.7	0.0181	0.0058	-6.365	-2,295,395	-672.3

EXHIBIT B5

Ductile Iron Pipe Heat Treating

$CH_4 + 2\ O_2$ ----> $CO_2 + 2\ H_2O$

$C_2H_6 + 3.5\ O_2$ ----> $2\ CO_2 + 3\ H_2O$

$CH_4 + C_2H_6 + 5.5\ O_2$ ----> $3\ CO_2 + 5\ H_2O$

Fuel Higher Heat Value	1,011	BTU/cf	
Fuel Composition (estimated):	*CH_4*	*97.8%*	vol/vol
	C_2H_6	*2.1%*	vol/vol
Basis (mole Fuel @ STP):	1.0	(68 F, 14.7 psia)	
Percent Excess Air:	10.0%		
Annual Natural Gas Consumption	100,000	Mcf	
Exhaust Temperature (T_1)	1,740	degrees F	
Exhaust Temperature (T_2)	300	degrees F	(assumed minimum practical)
Air to Fuel Ratio:	9.44	cf air/cf fuel	
Annual Operating Hours:	4,000	16 hr/d, 5d/wy, 50 wk/yr	

Heat Treat Inlet Stream Data

Species	**Stoichiometric Composition** (moles)	(mole fraction)	**Estimated Composition** (moles)	(mole fraction)	**Totals** (moles)	(mole fraction)
CH_4	0.978	0.086	0.978	0.0785	113,194,773	0.0785
C_2H_6	0.021	0.002	0.021	0.0017	2,430,563	0.0017
O_2	2.030	0.178	2.232	0.179	258,386,166	0.179
N_2	7.635	0.669	8.398	0.674	972,024,149	0.674
Air	9.664	----	10.631	----	1,230,410,315	----
H_2O (v)	0.747	0.065	0.822	0.066	95,151,731	0.066
Totals	11.41	1.00	12.45	1.00	1,441,187,381	1.00

EXHIBIT B5 (Continued)

Heat Treat Exhaust Stream Data (assumes complete fuel combustion)

Species	**Estimated Composition** (moles)	(mole fraction)	**Cp_{mean} @T_1*** BTU/(lb-mole*F)	**Cp_{mean} @T_1*** BTU/(mole*F)	**Cp_{mean} @T_2*** BTU/(lb-mole*F)	**Cp_{mean} @T_2*** BTU/(mole*F)
CO_2	118,055,898	0.082	11.78	0.025947137	9.451	0.020817181
N_2	972,024,149	0.674	7.443	0.016394273	6.988	0.01539207
O_2	23,489,651	0.016	7.909	0.017420705	7.184	0.015823789
H_2O (v)	328,832,964	0.228	9.138	0.020127753	8.154	0.017960352
Totals	1,442,402,662	1.000				

* Richard Felder, Ronald Rousseau, <u>Elementary Principles of Chemical Processes</u>, 2nd Edition, p351.

Results Summary for Ductile Iron Heat Treat Exhaust

Enthalpy @ T_1 BTU/(mole)	**Enthalpy @ T_2** BTU/(mole)	**Entropy @ T_1** (BTU/mole*R)	**Entropy @ T_2** (BTU/(mole*R))	**Exergy** (BTU/mole)	**Exergy** (BTU/hr)	**Exergy** (kW)
30.0	3.7	0.0255	0.0057	-15.754	-5,680,970	-1,663.8

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Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and great energy independence for America. By investing in technology breakthroughs today, our nation can look forward to a more resilient economy and secure future.

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- Conserve energy in the residential, commercial, industrial, government, and transportation sectors
- Increase and diversify energy supply, with a focus on renewable domestic sources
- Upgrade our national energy infrastructure
- Facilitate the emergence of hydrogen technologies as a vital new "energy carrier"

The Opportunities

Biomass Program
Using domestic, plant-derived resources to meet our fuel, power, and chemical needs

Building Technologies Program
Homes, schools, and businesses that use less energy, cost less to operate, and ultimately, generate as much power as they use

Distributed Energy & Electric Reliability Program
A more reliable energy infrastructure and reduced need for new power plants

Federal Energy Management Program
Leading by example, saving energy and taxpayer dollars in federal facilities

FreedomCAR & Vehicle Technologies Program
Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Geothermal Technologies Program
Tapping the Earth's energy to meet our heat and power needs

Hydrogen, Fuel Cells & Infrastructure Technologies Program
Paving the way toward a hydrogen economy and net-zero carbon energy future

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Boosting the productivity and competitiveness of U.S. industry through improvements in energy and environmental performance

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